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Nonlinear-optical correction of aberrations in imaging telescopes based on a diffraction structure on the primary mirror

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Introduction

This expert assessment is devoted to nonlinear-optical correction of distortions in primary mirrors of imaging telescopes with a special diffraction structure, which is applied to the surface of the primary mirror and allows one to form the light beam that carries information about optical quality of the telescope's primary mirror. Such telescopes are intended for obtaining high-quality image of the object or of the source and can be used as telescopic systems both for observation purposes and for formation of high-quality beams.

In Chapter 1 of the Report, we present a brief review of architectures of the telescopes with nonlinear-optical correction of the primary mirror's distortions. We consider, in particular, the telescopic systems of the 'bypass' configuration, telescopes with a diffraction structure, or diffraction optical element (DOE), on the primary mirror, and telescopes with DOE on the secondary mirror (the so-called 'hybrid' configuration). In the same chapter of the review we discuss advantages and drawbacks of the above configurations.

In Chapter 2 of the Report, we compare the compensation resources of the 'bypass' system with those of the telescope with the DOE on the primary mirror. Since the latter telescope system is the main object of this assessment, in Chapter 2 we analyze typical sources of residual errors of correction of the primary mirror's distortions in a telescopic system of this type.

Chapters 3 and 4 are devoted to problems of deposition of the DOE onto surface of the primary mirror, which can have, in particular, either segmented or deployable design.

Chapter 1.

Review of various telescope designs with nonlinear-optical correction for primary mirror distortions.

At present, much attention is paid world-wide to the research aimed at development of high-resolution telescopes with diameter of the primary mirror as large as tens of meters. These systems are intended for observation of both natural (astronomical) and artificial objects in outer space. Along with the function of observation, such telescopes can be used for formation of laser beams directed to outer space, e.g., for transport of radiation energy over super-large distances. The main requirement imposed on such systems is their high resolution, close to its diffraction limit, which is determined, primarily, by diameter and quality of the primary mirror. In the development of such mirrors, a great number of problems arises related to manufacturing of the mirror with needed quality, its delivery to the point of use, and maintaining the needed quality of optical surface during the period of its operation. Most promising in this respect is to use a segmented primary mirror, which, however, needs correction of its shape as a whole rather than only high quality of its separate components. This problem can be solved either by the linear adaptive methods or by methods of nonlinear optics [1÷33]. In this review, we consider application of methods of nonlinear optics.

In this field, two trends of research are being developed now, which use nonlinear-optical correction of the primary mirror's aberrations and are, in essence, fairly close to each other. The first of them has to do with the primary mirror's distortion compensation in the beam-forming systems. The role of corrector is played, in this case, by a system that performs phase conjugation (PC) [7,13÷15,17÷20,24]. In the second trend of research, the image is corrected by methods of nonlinear optics in observation telescopic systems, where the role

of corrector is played by an appropriate hologram [2÷4,8,10÷12,23,27÷29,33] or by a corrector using the negative optical feedback [6,22,31]. It is noteworthy that the observation systems can be either active, i.e., with laser-light illumination of the object, or passive, used for observation of luminous (or illuminated by natural light) objects.

The principle of operation of the correctors of this type is known fairly well and has been repeatedly discussed in the literature (see, e.g., [1,2,6,9]). In this section of the report, we will consider different architectures of the imaging systems.

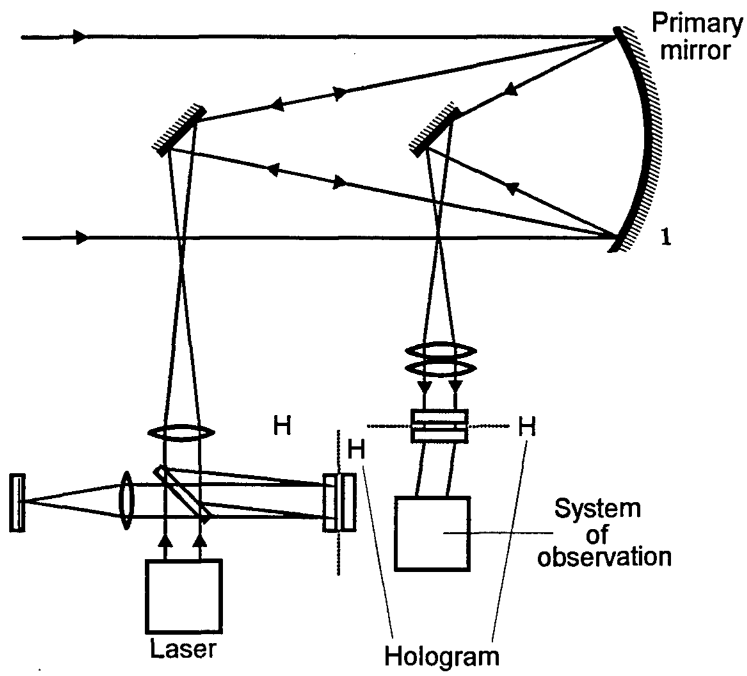


Fig.1.1. Schematic of the telescope with a static holographic corrector.

The principle of operation of the system with a hologram-corrector has been proposed in [1,2]. The feasibility of application of static hologram for correction of the primary mirror's distortions has been first shown experimentally by Yu.N.Denisyuk and S.I.Soskin [3]. In the optical configuration proposed by these authors (see Fig.1.1), the laser beam that carried information about distortions of the primary mirror was directed to the mirror from a point source placed in the curvature center of this mirror. At the

same time, the observed object was located at infinite distance, and its radiation was incident on the mirror in the form of a collimated beam parallel to the axis of the system. A specific feature of this system was necessity to move the hologram, after its recording on a photographic plate, into the channel of observation of the object. This kind of configuration, in which the radiation from the object and the radiation probing the aberrations are propagating to the primary mirror along different paths, received the name of "bypass" configuration [11,13].

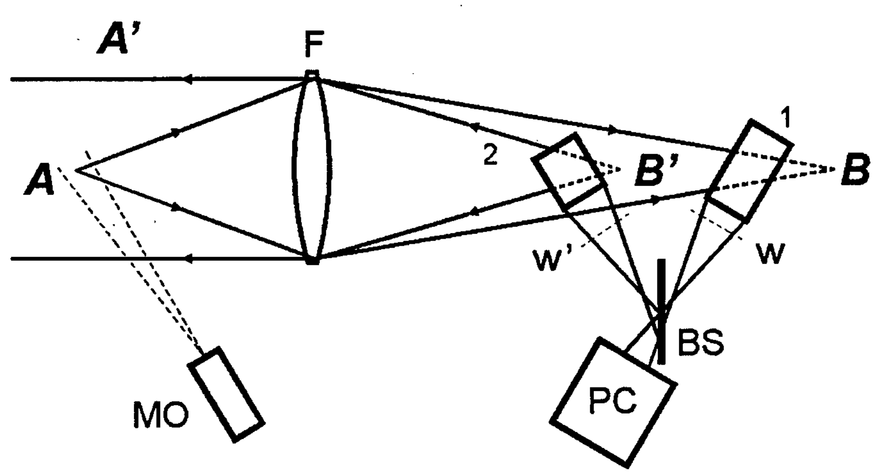


Fig.1.2. Illustration of principles of dynamic correction for distortions in the nonreciprocal ("bypass") system.
F - primary lens (mirror) being corrected, 1,2 - auxiliary optical systems of small light diameter and high optical quality, PC - phase conjugation mirror, A - object being imaged, A' - toward the corrected remote image of the object A, B and B' - distorted images of the object, W,W' - images of the primary lens (mirror) aperture, MO - master oscillator.

The idea of using the bypass configuration for imaging telescopes [13], where correction of distortions is performed by means of PC, is illustrated in Fig.1.2 (in this particular case - for the telescope forming image at infinity). In this system, the imaged object (A) is illuminated by coherent radiation of the master oscillator (MO). After passing through the lens F (or after reflection from the primary mirror), in the point B, the distorted image of the object is formed. By means of an auxiliary optical system 1 of high optical quality and small

diameter, the radiation is directed into the PC-mirror. The beamsplitter BS directs radiation with conjugated wavefront to the second auxiliary optical system 2 also of high optical quality and fairly small diameter. In point B', a poor quality image of the object is formed, whose radiation after second pass through the lens (or after reflection from the primary mirror) is collected at a specified (e.g., at infinite) distance from the lens. In this case, distortions of the principal element of the system are compensated, and the image of the object gains high quality. To compensate for distortions, the optical system formed by the two auxiliary systems and PC-mirror should restore the image of the principal lens at a scale of 1:1 (condition of self-projection) on the principal lens (or mirror) again.

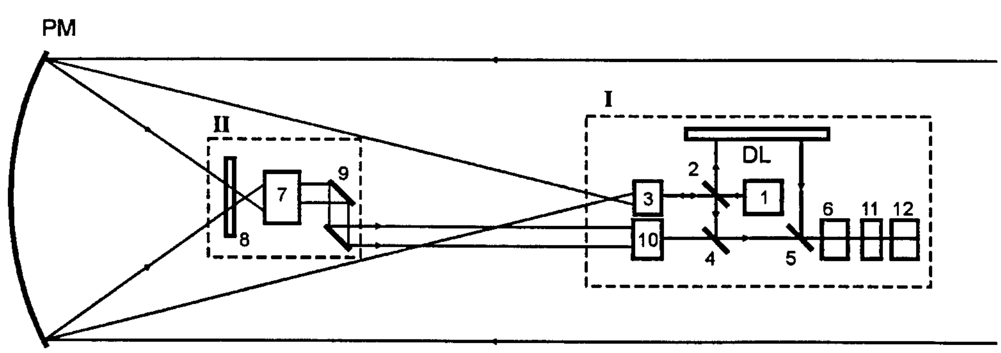


Fig.1.3. Telescopic system with a corrector based on a transmission dynamic hologram. PM - primary mirror, I, II - optical units, 1 - laser, 2,4,5 -beamsplitters, 3 - optical subsystem forming the beam, 6 - holographic corrector; DL - optical delay line; 7 - auxiliary optical subsystem, 8 - spectral filter; 9 - flat mirror, 10 - auxiliary optical subsystems,;11 - imaging system; 12 - detection system.

Schematic diagram of the observation system based on the bypass geometry with a transmitting hologram is shown in Fig.1.3. Due to supposed considerable dimensions of the primary mirror, all auxiliary optical systems, including the reference laser and service systems, can be located in compact regions in the vicinity of the curvature center (unit 1) and near the focal zone of the primary mirror (unit II), virtually with no shielding of the light beams.

Operation of this optical system can be commented as follows. The polarized beam of the reference laser 1 with an ultimately low divergence, after passing through semitransparent beamsplitter 2 and auxiliary optical system 3, illuminates the primary mirror of the telescope from its curvature center. After reflection from the primary mirror, the laser beam attains the wavefront distortions, caused by poor optical quality of the mirror, and goes back to unit 1, where a fraction of the quasi-plane probe beam, reflected by beamsplitter 2 and polarization beamsplitter 4, is branched out into the channel of dynamic corrector 6. The second part of emission of the reference laser, deviated by beamsplitter 2, is directed to the delay line DL and then to corrector 6, at a small angle to the probe beam. In this way, the corrector writes down a hologram that carries information about optical distortions of the primary mirror of the system.

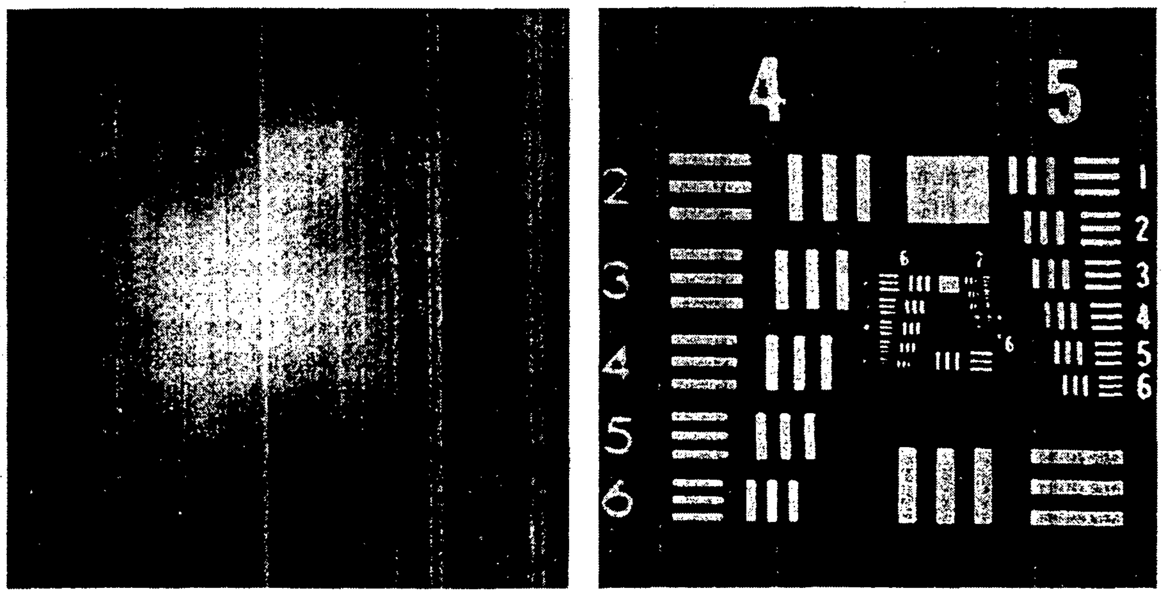
Auxiliary optical system 3, based on high-quality optical elements of fairly small size, should form the image of the primary mirror's plane in the plane of the corrector. Formation of the remote object image is made with the use of unit II. The radiation from the observed object reflected by the primary mirror passes through auxiliary system 7, which transforms it into a quasi-plane beam containing information about the object and distortions of the primary mirror. By means of plane mirrors 9, this beam is directed to the correction unit (I), where auxiliary system 10 (together with system 7) projects the image of the primary mirror into the plane of the hologram so that the image of the pupil of the primary mirror coincides completely with its image formed in this plane by system 3. Due to diffraction of this beam on the hologram-corrector to the minus first order, one can observe in the receiving system 16, by means of system 11, a corrected image of the object. It should be emphasized here that inaccuracy in superposition, in the corrector plane, of images of the primary mirror in the two channels mentioned above appears to be a possible source of

undercompensation for the effect of distortion of the telescope's primary mirror on quality of the image of the observed object.

In [14], a description is presented of one of the first experimental study of correction of the primary mirror's distortions using phase conjugation in a telescope based on the bypass configuration. In the course of the experiments, remote objects were observed whose images were formed by a 7-segment primary mirror 300 mm in diameter. The phase conjugation was performed with a four-wave mixing hypersonic mirror. As has been shown experimentally [14], the image quality remained close to the diffraction limited when separate segments were tilted by an angle of up to $40\lambda/D$ (λ-wavelength, D- diameter).

A drawback of such an observation system is related to necessity to illuminate the object by laser radiation, because observation of remote objects requires high power illuminating lasers. In the observation systems that use the hologram-corrector, the source of coherent radiation is needed only on the stage of hologram recording. A great deal of experimental studies are known at present devoted to these systems with holographic correctors. In some of them, static holograms recorded on photographic plates were employed [3÷5,8,10,12,23,28], while in others - dynamic holograms [27,29,30,33] based either on photorefractive crystals [27,33], or on liquid-crystal spatial light modulators (SLM) [29,30]. These studies have demonstrated ability of hologram to correct considerable aberrations of a large-size mirror and to obtain resolution close to the diffraction limit. Specifically, in [12], large distortions of a plastic mirror, 40 cm in diameter, were corrected by a static hologram nearly up to the diffraction limit. In [28] the bypass-type compact telescopic system with the primary mirror 0.9m in diameter and of curvature radius of 5.2m was employed, holographic correction being performed in the area of diameter of 0.45m. The phase distortions of the beam, reflected from the mirror, amounted to 100

wavelengths. The hologram-based correction resulted in that the spherical aberration due to the lens inserted at the stage of hologram recording was absent in the remote -object image. Fig. 1.4 shows photos of the test-object images, obtained before correction (a) and after it (b). Figure (b) exhibits resolution close to the diffraction limit (see column 7, line 3).



(a) (b)

Fig.1.4. USA Air Force resolution chart.
a - before correction (columns 2 and 3); b - after correction (the resolution being diffraction limited with bars resolved by column 7, line 3).

In [29], by using a SLM for recording the hologram of distortions of a thin 4-μm membrane mirror 15 cm in diameter, the mirror distortions giving rise to divergence of the beam exceeding the diffraction limit by a factor of 330, were reduced after the correction by more than a factor of 200. Considerable misalignment of a 6-segment mirror, 15 cm in diameter, with observation of a test-object illuminated by an incandescent lamp, were corrected in [33] using a volume dynamic hologram recorded in a photorefractive crystal. In studies on holographic correction, where the observed object was illuminated by a source with extended spectrum [10,12,27,30,33], the dispersion of the hologram was compensated by means of a special diffraction grating.

A fundamental drawback of the bypass system is related to incomplete distortion correction of the telescope's primary mirror by hologram due to different angles of incidence onto the primary mirror of the probe beam and beam from the object. In this system, Zeidel's aberrations arise. If, for example, the hologram is recorded from the curvature center of a spherical mirror, spherical aberration is absent, but it exists for observation of a remote object. For the beam-forming system with a PC-mirror, designed in the bypass configuration, this fundamental drawback also takes place. In addition, for the smallest possible length of the telescope, in the bypass configuration, the area in the vicinity of the curvature center of the mirror is usually used. For this reason, these systems are approximately twice as long as conventional telescopic systems, for the same aperture and speed.

Another way to build the telescope with distortion correction by methods of nonlinear optics is based on using a special diffraction optical element (DOE) on the primary mirror of the telescope. This method was independently suggested in [7,15,17] and checked experimentally in [15,17]. The system using the DOE has been mainly studied so far as applied to the beam-forming systems with corrections of aberrations of the primary mirrors by means of phase conjugation (see, e.g., the review paper in [32]). In the observation systems with holographic correction, this method, as far as we know, was used only in [24], where the DOE was applied to the secondary, rather than to the primary, mirror of the telescope.

Schematic diagram of the beam-forming telescope with PC-correction of the primary mirror's aberrations and aberrations of the double-pass system for amplification of laser radiation, with the DOE on the primary mirror, is shown in Fig.1.5. The system is operating in the following way: a high-quality master-oscillator's reference beam of needed power illuminates the primary mirror from point O located at some distance L from the primary mirror in the vicinity of the

secondary mirror of the telescope. The corresponding diffraction structure is applied to the primary mirror with the diameter D and curvature radius R. The beam is diffracted into the first diffraction order of the DOE and hits the PC-mirror. The wavefront of this beam has distortions caused by distortions of the primary mirror and amplification channel. After phase conjugation and further

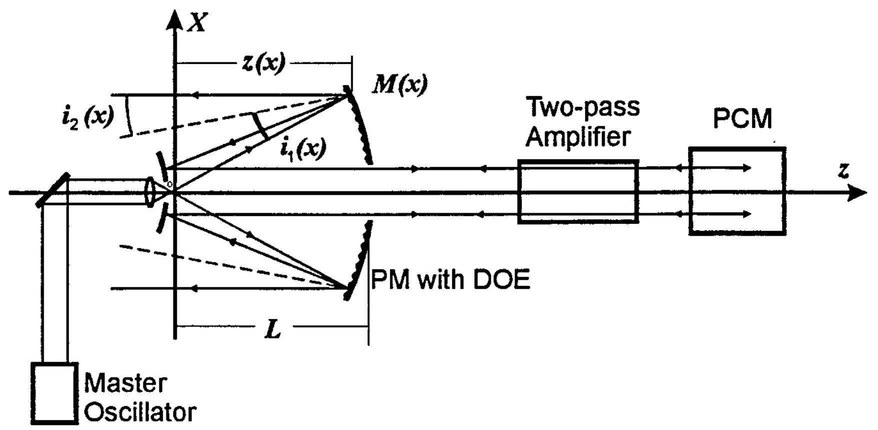


Fig.1.5. Beam-forming telescope with DOE on the primary mirror with the use of PC correction.

amplification, the beam travels back to the primary mirror, by which it is reflected in zeroth diffraction order. The distortions introduced by the primary mirror upon diffraction in the first and zeroth orders are almost the same. As a result, the distortions attained during the first pass through the telescope and amplifier are compensated on the way backward. In accordance with the principle of holographic correction of aberrations, the correction should be close to ideal, when arrangement of the "lines" of the diffraction structure on the mirror exactly corresponds to the interference pattern that would have been observed if the mirror were illuminated by a point source from point O (Fig.1.4) and by the wave conjugated with the one that is to be formed at the exit of the telescope. In this figure - it is a plane wave arriving to the mirror from infinity. In this case, the DOE has a form of concentric rings condensing toward the edge of the mirror, similar to the system of rings in Fresnel's zone plate. The

transverse coordinate x of the ring with a number $N(x)$ ($N = 1,2,3,...$) is determined by the relationship:

$$N(x)\,\lambda = \rho(x) - z(x) \tag{1.1}$$

where $\rho(x) = (x^2+z^2)^{1/2}$ is the radius-vector at the point M(x), $z(x) = (R^2-x^2)^{1/2} - R + L$, and λ is the radiation wavelength. In this case, the total number of the rings N_{max} on the mirror aperture and the minimum distance between the rings t_{min} are given, respectively, by

$$N_{max} \approx D^2/8\,L\lambda\,;\;\; t_{min} \approx 2\,L\lambda/D \tag{1.2}$$

The first experimental use of the DOE on the primary mirror in the system of mirror's aberration compensation by means of PC has been performed in [15,17]. Schematic of the experimental setup is shown in Fig.1.6.

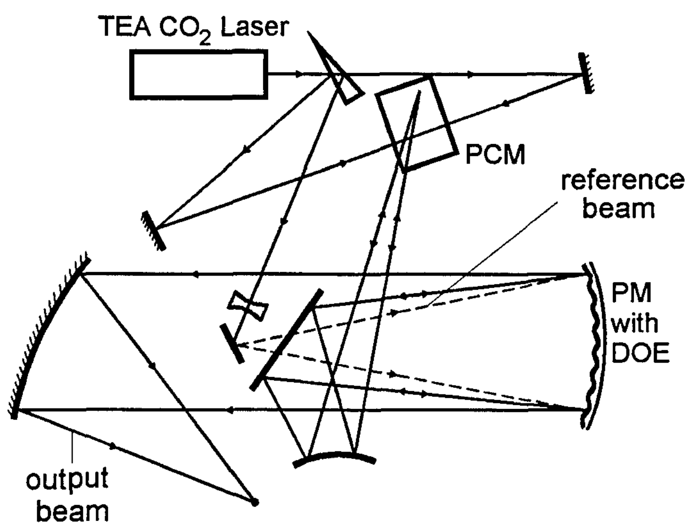


Fig.1.6. Optical schematic for demonstration of dynamic distortion correction with the use of phase conjugation in the beam-forming telescope with DOE on the primary mirror.

The reference TEA-CO_2 laser was operating on the fundamental transverse mode (divergence 1.3 mrad, repetition rate 40 Hz, energy per pulse ~ 3 J in the line P20). A fraction of the laser radiation was used to produce two counter-propagating beams for pumping the four-wave mixing phase-conjugation mirror (PCM) in a cell with the nonlinear medium SF_6. Diameter of the table-top telescope's primary mirror, with a magnification of $M = 5$, was $D =$ 120mm. The minimum period of the DOE applied to the surface of the primary mirror was t_{min} = 0.21 mm. The distance between the point source and the primary mirror was L=1.2 m. The probe beam with the energy close to 40 mJ was directed to the primary mirror, and 5% of its energy was reflected to the first diffraction order. Then, the radiation was reflected by the PC mirror with reflectivity equal to 200%. The phase-conjugated beam was then reflected by the primary mirror in the zeroth order, turned into a collimated beam, and entered the detection system, where the corrected image was observed with resolution close to that of the primary mirror diffraction limit (0.2 mrad). To check the possibility of compensation for dynamic aberrations, the primary mirror was tilted by some angle, which was varied linearly in time. For tilts of the mirror by the angles α up to $65\lambda/D$, the direction of the output beam remained the same, while its energy decreased twice due to vignetting of the beam on the primary mirror. The vignetting did not make it possible to find experimentally the limiting angles α within which the correction occurs.

Studies with the DOE on the primary mirror of the beam-forming telescope with PC-correction of distortions in the primary mirror and in amplification channels have been carried out also in [19]. In these experiments, both a stable direction of propagation and divergence of the beam at the telescope exit were observed for tilts of the primary mirror up to 0.5 mrad. The system was operating with radiation of a YAG-laser ($\lambda = 1.06$ μm).

Experiments with the use of the DOE on the telescope's primary mirror in observation systems with a holographic corrector, as was already mentioned, have not been described in the literature thus far. Still, we present in Fig.1.7 a possible schematic of such a system. This system reminds the beam-forming telescope, with PC effect used for the correction (Fig.1.5) and with DOE applied to the primary mirror.

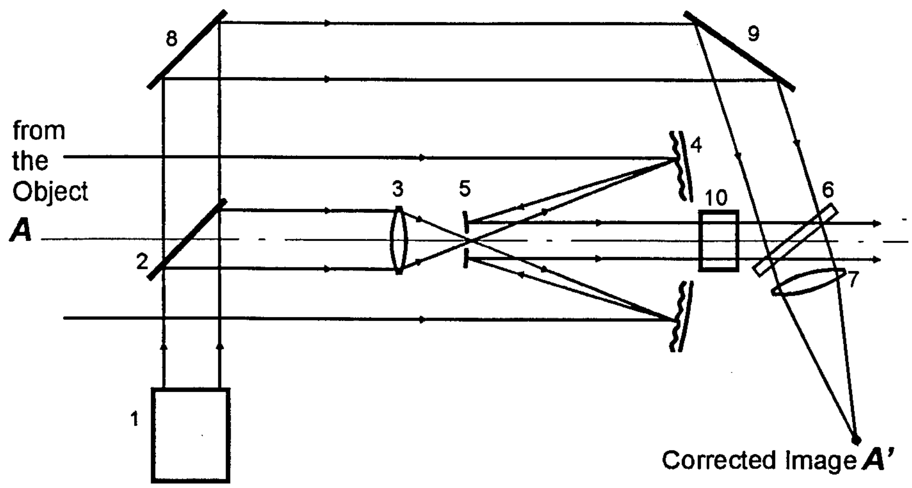


Fig.1.7. Optical schematic of the telescope with DOE on the primary mirror with the use of holographic distortion correction.
1 - laser, 2 - beamsplitter, 3,7 - lenses, 4 - primary mirror with DOE, 5 - secondary mirror of the telescope, 6 - holographic corrector, 8,9 - flat mirrors, 10 - optical system.

In the system shown in Fig.1.7, the image correction is made using the hologram recorded in nonlinear medium 6 by means of a properly delayed plane reference beam and a probe beam containing information about distortions of the primary mirror. The radiation of the beam from the observed remote object, incoherent with respect to the radiation recording the hologram, is reflected by the primary mirror with DOE in the zeroth diffraction order. The probe beam radiation is diffracted by the DOE in the first order. Then, the both beams are traveling toward the nonlinear medium along virtually the same direction. The corrected image of the object is observed in the direction of the reference beam,

with the object beam being diffracted by the hologram to the minus first diffraction order.

The system needs an auxiliary optical unit (10) that provides formation of the primary mirror's image in the hologram plane.

Essential restrictions to the use of DOE for aberration correction are related to technological problems of their fabrications on surfaces of large-size mirrors. At present, the diameter of one-piece mirrors with DOE on their surface does not exceed 500 - 1000 mm (in more detail, see Section 3).

The efforts to develop the system with a segmented primary mirror with the DOE on its surface faced a good deal of problems. In such a system distortions caused by errors of the diffraction structure will not be compensated. In development of the mirror with the DOE consisting of separate segments, one has, at the initial stage, to get into coincidence transverse positions of fringes of the diffraction structure of adjacent segments. For the large aperture ratio, when the distances between the lines near the edge of the mirror become comparable with the laser wavelength, the difficulties increase to such an extent that this type of system for aberration compensation becomes unrealistic. A possible solution of this problem has been proposed and verified experimentally in [25]. This solution was based on using dynamic, rather than static, diffraction element - holographic optical element (HOE) recorded in the light of an auxiliary laser. This method will be discussed in Sect. 4 of this report.

An essential advantage of the telescope system with DOE (or HOE) on the primary mirror is a shorter base length of the telescope as compared with the system of the bypass type. Recall that the minimum length of the telescope in the bypass configuration is of the order of the curvature radius of the primary mirror, whereas for the telescope with DOE, this characteristic length is determined by focal length of the primary mirror.

For correction of aberrations of the primary mirror of the beam-forming telescope with very large diameter of the mirror (tens of meters), inevitably comprising segments of large size, it has been suggested in [18] to use a hybrid method combining DOE with bypass configuration. These systems were called TENOCOM (Telescope with Nonlinear Optical Compensation). The Tenocom system is shown schematically in Fig.1.8. It works as follows: the reference beam from a point laser source illuminates the segmented primary mirror 1 from the point close to its curvature center. The beam reflected by the mirror, containing information about distortions of the mirror, hits small concave mirror 2 and, after lens 3, is directed to auxiliary convex mirror 4 and, then, to secondary mirror 5 of the telescope. To the surface of mirror 5, a special DOE-structure is applied, on which the light is diffracted in the first order so that the beam is directed to the PC-mirror. After reflection by the PC-mirror, the beam returns again to mirror 5, by which it is reflected in the zeroth order, then it is directed to concave mirror 1 and further to the output of the system. Parameters of all elements are chosen so that after reflection from secondary mirror 5, each ray comes back to the same point of the primary mirror's surface, from which it came out in the first pass (though at some other angle of incidence). As a result, the distortions of the mirror appear to be compensated significantly.

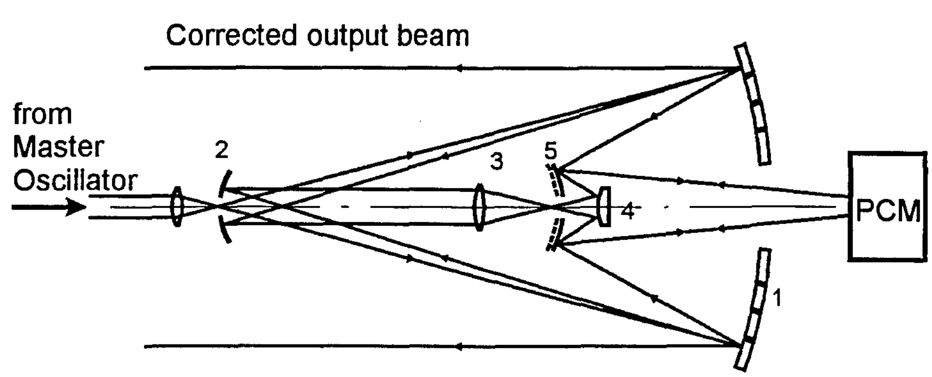


Fig.1.8. Beam - forming telescope with DOE on its secondary convex mirror with the use of nonlinear optical compensation for distortions (TENOCOM).

1 - primary mirror, 2 - concave mirror, 3 - lens, 4 - convex mirror, 5 - secondary convex mirror with DOE.

First experiments on compensation of the telescope's primary mirror aberrations in the TENOCOM configuration are described in [18]. In this system, TEA-CO_2 laser was used. Diameter of the 6-segmented primary mirror was 400 mm, with its focal length 2 m. The DOE was applied to the surface of the secondary mirror, 60 mm in diameter. Upon misalignment of the primary mirror's elements up to angles of $28\lambda/D$ and maximum longitudinal displacements of the segments with respect to each other (piston-shift) of 150λ, the PC compensation allowed one to retain the diffraction-limited beam quality at the exit of the telescope.

The TENOCOM configuration was also used in the observation telescope with correction of the primary mirror's aberrations by means of dynamic hologram [24].

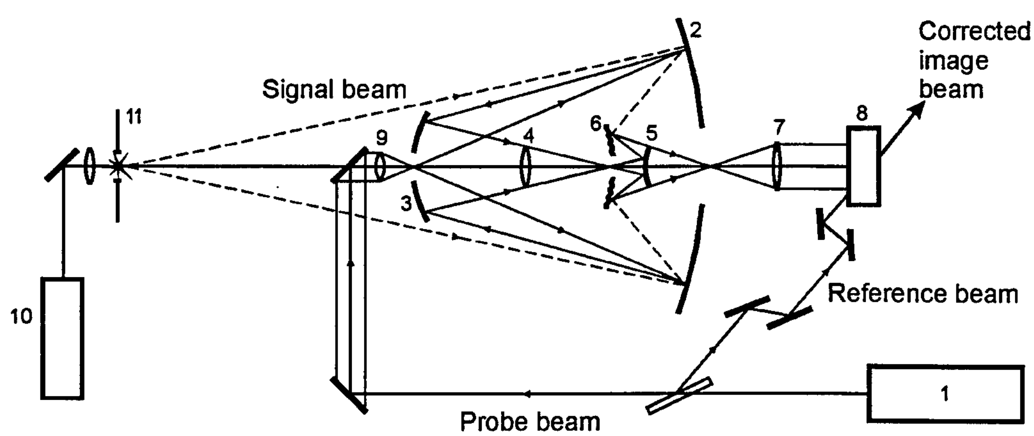


Fig.1.9. Schematic of the observing telescope with DOE on its secondary mirror with the use of holographic correction for distortions of the primary mirror.
1 - laser for recording a hologram, 2 - primary mirror, 3 - concave mirror, 4,7,9 - lenses, 5 - convex mirror, 6 - secondary mirror with DOE, 8 - hologram, 10 - laser for illumination of an object.

Schematic of the setup is shown in Fig.1.9. In this system, the radiation of a repetitively-pulsed CO_2 laser (1) running in linear polarization on the fundamental mode at the line 10P(20) of CO_2 was used. The energy of a pulse,

with a pulsewidth of 12 μs, was 5 J. The volume dynamic hologram was recorded in the nonlinear medium SF_6 (200 - 600 Torr) in cell 8, 1 cm thick. The plane reference beam participating in recording of the hologram was transmitted through the delay line. The probe beam bearing information about aberrations of primary mirror 2 was formed in the following way: the laser radiation, passed through lens 9, formed a point source in the plane near the curvature center of the primary 6-segmented mirror (2) with a diameter of 400 mm and focal length of 2 m. After reflection from the primary mirror 2 and from auxiliary concave mirror 3, and after passing through lens 4, the radiation was reflected by convex mirror 5 and was diffracted, in the first order, by the DOE applied to the secondary mirror of the telescope (6). Then the radiation was directed, by lens 7, to the cell with nonlinear medium (8) where this radiation, together with the reference beam, recorded the dynamic hologram. The angle between the interfering probe and reference beams was 30 mrad, so that the period of the hologram was about 350 μm. Optical elements 3 - 7, placed between the primary mirror and cell 8, formed the image of the primary mirror 30 mm in diameter in the plane of the hologram. In these experiments, a remote object was observed (an aperture of small diameter at a distance of 12 m from the primary mirror, illuminated by laser 10, incoherent with respect to laser 1). The radiation of this object, "read out" the hologram after reflection from the primary mirror and then from DOE on secondary mirror 6 in the zeroth diffraction order. The radiation from the object created the image of the primary mirror in the nonlinear medium coincident with the image (of the same size of 30 mm) formed by the beam that read out the aberrations. Polarization of the object beam was perpendicular to polarization plane of the beams recording the hologram. Therefore, it was possible, by means of polarization technique, to distinguish between the object beam diffracted on the hologram and the reference beam transmitted by the hologram in the same direction. The

diffracted beam was focused by the lens in the plane of observation of the corrected object image. It was possible, simultaneously, to observe the distorted image of the object in the object beam transmitted through the hologram in zeroth diffraction order. Both images were photographed simultaneously on a conventional photographic plate using an auxiliary white-light source and method of thermal sensitization of the photo layer. The angular size of the aperture that simulated a remote object was $5.5 \cdot 10^{-5}$ rad, which approximately corresponded to the angle of $2\lambda/D$ (where D = 400 mm). All the segments of the mirror were tilted by angles of ~ $8\lambda/D$ with respect to their aligned positions. In spite of these aberrations, the size of the corrected image was close to its diffraction limit.

An essential characteristic of the telescope with holographic correction is related to losses of radiation in the observation system. These losses are controlled by diffraction efficiency of the hologram and DOE, and by a number of other characteristics of elements of the system. In this system, the probe beam energy, in the plane of the hologram, was 13 mJ, the reference beam energy - 3.3J, with beam diameters of 30 mm. Total energy density was close to that of saturation for $^{34}SF_6$. The energy of the object beam incident on the hologram was 360 mJ, while the energy coming out of it in the first diffraction order was 15 mJ, i.e., the diffraction efficiency was ~ 4%. Actually, the diffraction efficiency inside the cell was higher but reduced due to absorption in the medium.

For clearness, possible configurations of telescopic systems with nonlinear optical correction of the primary mirror's distortions, which are discussed nowadays in the literature, are presented in the Table 1.1.

Table 1.1.

	Beam-forming telescopes	Observation telescopes with laser-illuminated object	Passive observation telescopes
Bypass system	[13,11]	[13,14,20]	[3,4,8,10,12,23,27÷29,33]
DOE on primary mirror	[25*,19]	[15,17]	No experimental studies are available
Hybrid system (TENOCOM)	[18]	[24]	[24]

* Phase-matching of the mirror elements was made with dynamic HOE.

As seen from the table, the passive observation telescopic systems with the DOE on the primary mirror, intended for observation of natural luminous or artificially illuminated objects, have not been studied experimentally.

Completing this brief review of systems of aberration correction of the observation telescope's primary mirror using methods of nonlinear optics, we would like to note the following points.

The results of experiments carried out in systems with different architecture (bypass system, system with DOE on the primary mirror or hybrid system) show a fairly high quality of correction of distortion of the most complex and expensive element of the telescope - its primary mirror. In the telescope with the DOE on the primary mirror, compensation for distortions of the secondary mirror is also possible. For the DOE used in the beam-forming telescope with a PC-mirror, such a compensation will be complete because the direction of the output beam always coinsides with that to the probe beam source. In the observation telescope with DOE, a partial compensation for the secondary mirror's distortions is possible in a small field of view of the telescope, the full compensation being obtained in the direction at the probe beam source.

However, all considered systems, generally, are rather complicated and contain a number of high quality optical elements (though of small size as compared with that of the primary mirror). They can have large radiation losses related, e.g., to low diffraction efficiency of the hologram-corrector or DOE. Application of the DOE requires a fairly complex technique for its fabrication. In the high-power beam-forming systems with the DOE on the primary or the secondary mirror, there are the problem of breakdown in the beam necking during the backward pass of the beam through the DOE and the problem of protection of the oscillator from the beam propagating in the backward direction. These problems can be partly removed provided that the PC-mirror reflects the beam at somewhat shifted wavelength of the reference laser. In this case, unfortunately, the compensation fidelity appears to be lower. Still, all the systems employed can provide a high, though fundamentally limited, aberration correction factor. In spite of all the drawbacks mentioned above, these systems can be considered as a new great stride forward in technology of telescopes of high-resolution.

Chapter 2.

Evaluation of compensation capabilities of telescopes with the diffraction optical elements (DOE) on the primary mirror.

The resources to compensate for distortions of a telescope's primary mirror by means of nonlinear optical correction in systems with a PC-mirror (beam-forming telescopes) or with a holographic corrector (observation telescopes) can be analyzed using computer calculations with software providing summation of different rays propagating through the telescope. At the same time, evaluation of functional efficiency of such systems can be made by means of a simple and clear physical consideration of a residual distortion of the beam wavefront after the correction. Estimates of this kind we consider in this section of the report.

In evaluation of potentialities of aberration compensation in the telescope's primary mirror by methods of nonlinear optics, it is usually assumed that the hologram-corrector does not have any aberrations, and the phase conjugation, in the beam-forming systems, is performed perfectly.

A characteristic feature of the considered systems of holographic correction, based on the "bypass" configuration or using the DOE on the primary mirror, is that the wavefronts of the beam "reading out" the aberrations and of the beam from the object, when approaching the mirror, are characterized by different shapes. In similar systems with PC-correction, the wavefronts that differ in shape are those of the beams incident on the primary mirror in the first pass and in the pass backward after the PC procedure.

In the systems based on the bypass configuration, the image of the primary mirror is formed in the plane of the corrector (or of the PC-mirror) and, as has been noted in Chapter 1, this is performed both in the channel of "read-out" of the mirror distortions and in the distortion correction channel. In the corrector, where these images are brought into coincidence, one and the same deviation $\delta(x)$ of the real shape of the compensated mirror from the computed one results for different

wavefronts in deformations of different magnitude, which is the reason of fundamentally unavoidable residual errors in compensation. This situation is illustrated by Fig. 2.1.

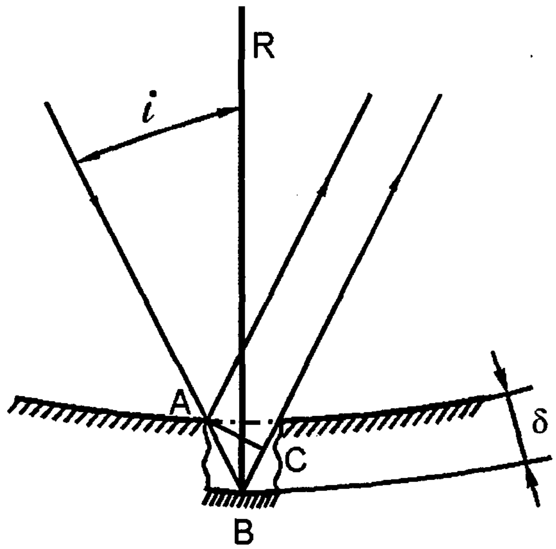


Fig.2.1. Path difference Δ between the ray reflected by the deformed mirror's surface (point B) and the ray reflected by the perfect mirror's surface (point A).
i - the incidence angle of the ray, R - normal to the mirror's surface at point B.
Δ=AB+BC=$2\delta cos(i)$
(AB=$\delta/cos(i)$, BC=$\delta cos(2i)/cos(i)$).

As seen in the figure, a local deformation of the wavefront of the beam reflected from the mirror's surface at a point $M(x)$ (for simplicity, we consider the two-dimensional case) at an angle of i, appears to equal $2\delta(x)cos(i)$. It follows herefrom that the undercompensated phase error in the correction system will be determined by the phase difference between the beams reflected by the mirror when reading the distortions and when observing the object:

$$\Delta\phi_1(x) - \Delta\phi_2(x) = 2\pi \times 2\delta(x)\left(\frac{cos\, i_1}{\lambda_1} - \frac{cos\, i_2}{\lambda_2}\right) \qquad (2.1)$$

where $i_1(x)$ and λ_1 are the angle of incidence of the beam onto the primary mirror in point $M(x)$ and the wavelength upon detection of distortions; $i_2(x)$ and λ_2 are the same parameters upon observation of the object.

For evaluating the degree of correction of distortions of the telescope's primary mirror, it is helpful to introduce the local compensation factor defined by the relationship

$$m(x) = \frac{\Delta\phi_2(x)}{\Delta\phi_1(x) - \Delta\phi_2(x)} = \frac{\cos i_2(x)}{\lambda_2\left(\frac{\cos i_1(x)}{\lambda_1} - \frac{\cos i_2(x)}{\lambda_2}\right)} \qquad (2.2)$$

The coefficient $m(x)$ has a simple physical meaning. It shows how many times the quantity that controls the image quality - the deformation of the beam wavefront in point x after correction - is reduced compared with initial deformation that was "read out" from the mirror.

We will first estimate the errors of compensation of local deformations of the mirror by the hologram-corrector in the observation telescopic system with the bypass configuration. In a similar way, such errors have been estimated in a number of papers (see, e.g., [3,10,22,26,27]). Without the loss in generality, we will restrict ourselves to analysis of telescopes with small aperture ratio, when $D/F \ll 1$ (D and F are the diameter and focal length of the primary mirror).

For the smallest possible length of the telescope in the bypass configuration, $i_1=0$, while in observation of, say, a remote object, $i_2 \sim x/R$, where R is the curvature radius of the mirror. Then, the approximate expression for the compensation factor m, when $\lambda_1 = \lambda_2$, gains the form

$$m(x) = \frac{\cos i_2(x)}{1 - \cos i_2(x)} \approx \frac{1 - \frac{1}{8}\frac{x^2}{F^2}}{\frac{1}{8}\frac{x^2}{F^2}} \qquad (2.3)$$

Note that in a near-axis region, where $x \rightarrow 0$, the value m tends to infinity, i.e., the distortions appear to be totally compensated.

The compensation factor has the smallest value at the edge of the mirror ($|x| = D/2$):

$$m^{bypass}{}_{min} = \frac{1 - \frac{1}{32}A^2}{\frac{A^2}{32}} \qquad (2.4)$$

where $A = D/F$ is the aperture ratio of the mirror.

If the beam from the object is not propagating along the axis of the system, but makes a small angle Δi with the axis in the plane of incidence, then $i_2 \approx \frac{x}{2F} + \Delta i$ and

$$m^{bypass}{}_{min} = \frac{1 - \frac{A^2}{32} - \frac{A}{4}\Delta i}{\frac{A^2}{32} + \frac{A}{4}\Delta i} \qquad (2.5)$$

If the beam is deviated from the axis by the angle Δi in the plane perpendicular to the plane of incidence, then

$$i_2 \approx \sqrt{\left(\frac{x}{2F}\right)^2 + (\Delta i)^2}$$

and

$$m^{bypass}{}_{min} = \frac{1 - \frac{A^2}{32} - \frac{1}{2}\Delta i^2}{\frac{A^2}{32} + \frac{1}{2}\Delta i^2} \qquad (2.6)$$

As is evident from (2.6), the fidelity of correction, in this case, is deteriorated to a smaller degree than for the same Δi in the plane of incidence. In reality, the angles Δi can be determined by the field of view of the system.

If the quantities that differ are the wavelengths λ_1 and λ_2 of the beam "reading out" the mirror errors and the beam from the observed object, rather than their angles of incidence on the mirror, the correction of distortions also appears to be incomplete. In this case,

$$m \approx \frac{\lambda_1}{|\lambda_2 - \lambda_1|}$$

Consider now possibility to compensate for primary mirror's local errors in the telescope with holographic correction, when the beam containing information about distortions of the mirror is formed by the DOE applied to its surface. As before, we assume, for simplicity, that the wavelengths of the beam probing the errors of the mirror and of the beam from the object are the same ($\lambda_1 = \lambda_2$).

If $i_1(x)$ is the angle of incidence of the probe beam at the point $M(x)$ on the surface of the mirror, and $i_2(x)$ is the angle of incidence of the beam from the object at the same point (see Fig. 1.5), then the local compensation factor is determined, according to (2.2), by the relationship

$$m(x) = \frac{\cos i_2(x)}{\cos i_1(x) - \cos i_2(x)} \qquad (2.7)$$

For a small aperture ratio of the telescope, with the remote object on the axis of the system, we have $i_2(x) \sim x/2F$ and $i_1(x) \sim x/L - x/2F$. Then m acquires the form

$$m(x)^{DOE} \approx \frac{1 - \frac{x^2}{8F^2}}{\frac{x^2}{8F^2}\frac{4(L-F)F}{L^2}} \qquad (2.8)$$

and

$$m^{DOE}{}_{min} \approx \frac{1 - \frac{A^2}{32}}{\frac{A^2}{32}\frac{4(L-F)F}{L^2}} \qquad (2.9)$$

As follows from (2.9), at $L = F$ the errors of the mirror, in the approximation considered, are compensated completely ($m \to \infty$) not only at $x \to 0$, as in the bypass configuration, but at any x. This is fairly natural, since in this case the angles of incidence on the mirror both of the beams "reading out" the distortions and correcting the images are the same. It follows from (2.9) also that at $L=2F$, the smallest value of the compensation factor m is equal to that in the bypass configuration. At other values of the F/L ratio, $m_{min}{}^{DOE}$ can be by a factor of $L^2/(4F/L-F/)$ larger than that in the bypass system (see solid curves in Fig. 2.2). The figure illustrates also (dashed curve) the F/L function of a normalized by $A^2/32$ residual distortion $4(L\text{-}F)F/L^2$ in the case of DOE applied to its surface. In addition, as was already pointed out, the telescope in the configuration with DOE appears to be twice shorter than that in the bypass configuration. For this reason, the system with the DOE can be preferable for the use.

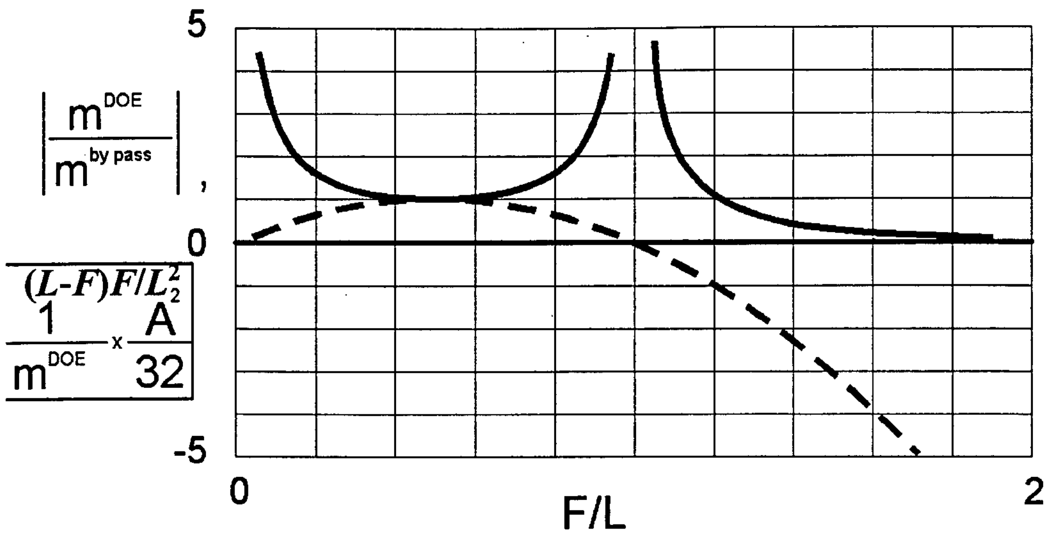


Fig. 2.2. F/L behavier of m_{min}^{DOE} to m_{min}^{bypass} ratio and of normalized residual distortion 4(L-F)F/L^2 of the beam front in telescope with DOE on the primary mirror.

It is noteworthy, finally, that there is no compensation for spherical aberrations in the bypass system, whereas in the system with the DOE on the primary mirror, the spherical aberration is compensated. This can be accounted for by the example of the system with PC-correction using Fig. 1.5 [32] (a similar result can be obtained with the use of the holographic corrector in observation optical systems).

The phase distribution of the beam, "reading out" the distortions on the surface of the mirror, has the form:

$$\varphi_0(x) = \frac{2\pi}{\lambda}\rho(x), \qquad (2.10)$$

where $\rho(x)$ is the distance between the point source O and the point $M(x)$ on the mirror surface, equal to

$$\rho(x) = \sqrt{x^2 + z^2} \qquad (2.11)$$

and

$$z(x) = \sqrt{R^2 - x^2} - R + L, \qquad (2.12)$$

where R is the curvature radius of the mirror and L is the distance between the point source and the mirror (see Fig. 1.5).

The phase distribution $\varphi_1(x)$ of the beam diffracted by the DOE into the first diffraction order differs from that in zeroth order by the value $2\pi N(x)$, i.e.,

$$\varphi_1(x)=\varphi_0(x)-2\pi N(x), \qquad (2.13)$$

where the number of the fringe of the grating $N(x)$ in the point $M(x)$ is given by the formula

$$N(x)\lambda=\rho(x)-z(x)\ . \qquad (2.14)$$

After that the diffracted beam travels to the PC-mirror, is phase conjugated, and then travels backward, the distortions arising along this path are compensated. Thus, the phase distribution $\varphi_2(x)$, in the beam incident on the mirror again, will be given by $-\varphi_1(x)$.

The phase distribution at the exit of the telescope, at the OX plane, is obtained by adding the phase $2\pi z(x)/\lambda$ to $\varphi_2(x)$.

Thus, the phase distribution in this plane at the exit of the telescope has the form

$$\varphi_{out}(x)=-2\pi\rho(x)/\lambda+2\pi N(x)+2\pi z(x)/\lambda\ . \qquad (2.15)$$

By substituting the formula for $2\pi N(x)$ from (2.14) into (2.15), we obtain

$$\varphi_{out}(x)=-2\pi\rho(x)/\lambda+2\pi\rho(x)/\lambda-2\pi z(x)/\lambda+2\pi z(x)/\lambda=0\ .$$

It means that, in the absence of deformations in the diffraction structure, with its fixed arrangement with respect to the reference source O, the wavefront of the output wave appears to be plane.

In the case considered above, a spherical mirror was used, and the fact, that the output beam of the system was plane, indicated compensation for spherical aberration, which is impossible in the bypass configuration, with distortions of the mirror being read out from its curvature center (see Chapter 1).

When the deformations of the primary mirror arise, e.g., due to vibrations, so that the quantities $\rho(x)$ and $z(x)$ take the values $\tilde{\rho}(x)$ and $\tilde{z}(x)$, the phase distribution at the exit of the telescope, which can be considered as a correction error gains the form

$$\varphi(x)_{out} = \frac{2\pi}{\lambda}[\rho(x) - \tilde{\rho}(x) - z(x) + \tilde{z}(x)], \qquad (2.16)$$

where $\rho(x)$ and $z(x)$ are given by formulas (2.11) and (2.12). In the case that the nonlinear-optical corrector (PC-mirror or dynamic hologram) exhibits a noticeable inertia with a characteristic time lag of Δt, an additional error of compensation will arise given by the formula

$$\varphi(x,t)_{out} = \frac{2\pi}{\lambda}[\rho(x,t) - \tilde{\rho}(x,t+\Delta t) - z(x,t) + \tilde{z}(x,\Delta t)]. \qquad (2.17)$$

As examples, let us consider typical deformations in the telescopic system and estimate the values of relevant residual errors [32]. As before, we consider correction of distortions using PC in configuration with DOE on the primary mirror.

1) Let the mirror with the DOE be ttilted by a small angle $\alpha = h/R$ around the axis perpendicular to the xz-plane, which passes through the point $x = 0, z = L$ (Fig.1.5).

For $\alpha \langle\langle \sqrt{\frac{2L}{\lambda}}$, the transverse coordinate of the DOE fringes can be considered to be constant. It can be shown, using (2.16), that in this case

$$\varphi_{out} \approx \frac{2\pi}{\lambda}\alpha\frac{x^3}{2L^2}. \qquad (2.18)$$

It follows herefrom that the residual error arising due to tilt of the mirror is smaller than the initial disalignment by a factor of $2L^2/x^2$ and, hence, appears to be virtually compensated.

Assuming that the greatest tilt of the wavefront should not exceed λ/D and taking into account that the residual error at the exit of the telescope is the greatest

at $|x|=D/2$ (see (2.18)), we can estimate the maximum admissible tilt of the primary mirror:

$$\alpha_{\max} \leq \frac{8L^2}{3D^2}\frac{\lambda}{D}. \tag{2.19}$$

It follows from (2.18) that in the systems with small aperture ratio, the primary mirror can be tilted to a much greater extent than the value determined by the diffraction limit. The main restriction for misalignment of the primary mirror, in such systems, is likely to be imposed by vignetting inside the system.

2) Consider now the effect of small variations of the primary mirror's curvature, which can be caused, e.g., by thermal effects or by inaccuracy in adjustment of the elastic thin-film mirror.

We represent variation of the mirror surface curvature in the form

$$\Delta\rho = \frac{1}{R} - \frac{1}{\tilde{R}}. \tag{2.20}$$

Using (2.16), we can obtain the approximate formula for the residual error

$$\varphi_{out}(x) \approx \frac{2\pi}{\lambda}\Delta\rho\frac{x^4}{4L^2}. \tag{2.21}$$

As in the case with the tilt of the mirror, the residual error arising due to variations of the mirror curvature is smaller than the initial one by a factor of $2L^2/x^2$.

Assuming the admissible tilt of the beam at the edge ($|x|=D/2$) to be λ/D, we obtain the admissible value of sagging:

$$S_{\max} \langle \frac{\lambda L^2}{D^2}. \tag{2.22}$$

It follows herefrom that in the considered system with a small aperture ratio, much larger variations of the mirror curvature are admissible than those in the system with no correction.

3) Let us estimate the residual error at the exit of the telescope, caused by thermal expansion of the primary mirror. In this case, the transverse coordinate x

increases due to increasing temperature (ΔT) approximately by the value $\Delta x=\chi\Delta T$, where χ is the thermal expansion coefficient.

It follows from (2.16) that the residual error is read as

$$\varphi_{out}(x) \approx \frac{2\pi\chi\Delta T x^2}{\lambda L}. \tag{2.23}$$

Based on the condition that the greatest tilt of the wavefront, at the edge of the mirror, should not exceed λ/D, we can estimate the admissible increment of diameter of the mirror ΔD:

$$\Delta D \leq \frac{1}{2}\frac{L\lambda}{D}. \tag{2.24}$$

As follows from (1.1), the increment in the diameter should not exceed half the distance between the fringes of the DOE at the edge of the mirror.

4) In the case when the distance between the point source and the mirror is changing, the curvature of the wavefront at the exit of the telescope is changing as well.

Let $\tilde{L} = L - \delta$, where $\delta << L$. It can be shown, using (2.14), that to within the lowest-order terms

$$\varphi(x)_{out} = \frac{-2\pi x^2\delta}{\lambda 2L^2} + \frac{2\pi}{\lambda}\frac{x^4\delta}{8R^2L^4}(R-L)(3R-L). \tag{2.25}$$

As is seen from this equation, with no allowance for the second term, that at the exit of the telescope we have a converging spherical wave with a focal length of

$$f=L^2/\delta\ . \tag{2.26}$$

Note that decreasing distance between the source and the mirror gives rise, in a conventional system, to appearance of diverging, rather than converging, wave.

The second term in (2.25) shows aberrations of this wave. As in previous estimates, we can obtain the greatest admissible values of δ that do not produce noticeable errors at the edge of the mirror:

$$\delta_{\max} \leq \frac{16L^4\lambda R^2}{D^4(R-L)(3R-L)} \qquad (2.27)$$

so that

$$f_{\min} \geq \frac{L^2}{\delta_{\max}} \qquad (2.28)$$

is the smallest focal length, which still does not produce any essential distortion of the wavefront.

When the system, in its initial state, is aligned to observe an infinitely remote source, the geometric divergence of the output beam, for a detuning of δ, equals $D\delta/L^2$. By equating this quantity to λ/D, we obtain condition for indifference of the system to longitudinal translations (δ) of the point source

$$|\delta| \leq \frac{L^2}{D^2}\lambda . \qquad (2.29)$$

5) Estimate now feasibility to control the beam direction, e.g., at the exit of the beam-forming telescope. Variations in this direction are related to transverse shift (H) of the point source. We assume that $H << D < L$.

Using the methods of evaluation, similar to those used above, we obtain the formula for the phase error

$$\varphi_{out}(x) \approx \frac{2\pi}{\lambda}\left(\frac{Hx}{L} + \frac{Hx^3}{2RL^2}\right). \qquad (2.30)$$

It follows from (2.30) that at the exit of the telescope, for such a shift of the source, the beam is deflected by the angle $\vartheta = H/L$. Within the same assumptions, using the formula for the second term in parentheses, we can obtain the value ϑ_{max}, which still does not deteriorate noticeably the beam quality:

$$\vartheta_{\max} \leq \frac{8R\lambda}{3D^2}\frac{\lambda}{D}. \qquad (2.31)$$

If the reference source is positioned in the vicinity of the telescope's secondary mirror, i.e., the length of the telescope equals L, then $R = 2LM/(M-1)$, where M is the telescope magnification. The field of view of the system, in this case, is

$$|\Delta\vartheta| \le \frac{16M}{3(M-1)}\left(\frac{L}{D}\right)^2\frac{\lambda}{D}. \qquad (2.32)$$

The experiments described in [9,10] have shown agreement between variations of the output beam direction versus H and estimates obtained from (2.30).

6) The restrictions in the correction accuracy also arise, in the system under study, due to dispersion of the diffraction element. For a finite bandwidth of the point source spectrum, the beams with different wavelengths are propagating, after diffraction on the DOE, in different directions, each spectral component, after the PC, traveling backward along its own path and being reflected by the mirror at its own angle.

At the edge of the mirror, the difference between the diffraction angles $\Delta\psi$ for the beams with the wavelengths differed by $\Delta\lambda$ equals $\Delta\psi \cong \Delta\lambda/t_{min} = D\Delta\lambda/2L\lambda$. The requirement $\Delta\psi < \lambda/D$ entails restriction imposed on the coherence length l_{coh} due to finite spectral width of the radiation:

$$l_{coh}=\lambda^2/\Delta\lambda>D^2/2L.$$

Summarizing evaluation of possible accuracy of correction of the beam-forming telescope's primary mirror errors, note that this kind of treatment can be applied also to configurations of observation telescopes with a hologram-corrector and allows one to obtain similar results.

In this section, we have analyzed fundamental restrictions of compensation resources of the considered systems. In practice, there are some additional technical factors that also contribute to deterioration of the compensation fidelity.

In the DOE-based system, such deterioration can be related, e.g., to errors of fabrication of the diffraction structure, which cannot be compensated, or to distortions of the structure because of stretching of the thin-film mirror.

The factors that reduce compensation potentiality of the system can be related also to aberrations of auxiliary optical systems and to errors in alignment.

It is noteworthy that in the system with the DOE on the primary mirror (like in the bypass system), when the observed object is characterized by a broad spectrum, the main errors can be caused by the width of the spectrum ($m \approx \lambda/\Delta\lambda$). In this case, the advantages of the system with the DOE can appear to be of no importance.

In real systems, the compensation potential can be noticeably restricted by vignetting, which restricts the field of view of elements of the system.

The main problem, in development of the imaging telescope with DOE on the primary mirror, is likely to be related to applying the diffraction structure to the surface of the large-size mirror.

In subsequent sections, we will present the current state of the art in development of different technologies of the DOE.

Chapter 3.

Review of techniques for producing DOE on the surface of mirrors.

As has been shown in Chapter 1, in telescopes with nonlinear-optical correction of distortions, it is necessary to form the light beam that carries information about optical distortions of the surface of the telescope's primary mirror. In this case, the borrowing of a fraction of the light beam incident on the mirror for the recording channel of the corrector can be made using a periodic or quasi-periodic diffraction structure applied to the surface of the mirror. This structure can be considered as a diffraction optical element (DOE) [34].

When applying the DOE to the surface of the mirror, one has to meet a number of requirements imposed on its energetic and aberration characteristics [35]. Among them, first of all, should be mentioned the diffraction efficiency of the DOE in the first diffraction order, needed to record the corrector, and the greatest possible diffraction efficiency in zeroth order (specular reflection) used in the image channel. In addition, the diffraction structure, applied to the surface of the primary mirror, should not noticeably distort the beam.

The energy and aberration characteristics of the DOE are closely connected with the DOE technology. At present, three main methods of DOE fabrication are known: (i) method of direct ruling of the diffraction structure [36], (ii) photolithography [34, 37], and (iii) physical holography [38].

Before proceeding to the review of technology of DOE fabrication by these methods, we will briefly discuss the main geometrical parameters of the diffraction structure on the surface of the primary mirror in the imaging telescopes.

A schematic of the optical telescope with DOE on the primary mirror is shown in Fig. 1.4. Operation of this system is described in detail in Chapter 1.

To obtain the beam carrying information about optical quality of the primary mirror, the mirror is illuminated by a beam emerging from point O positioned at some distance L from the mirror. An interesting case of this geometry is when L equals the focal length of the primary mirror (see Chapter 2). The spherical wave, emerging from its focus, after diffraction on the DOE in the first order with subsequent reflection from the mirror, is collected in point O, while in zeroth diffraction order it has the form of a plane wave.

The arrangement of the lines in the DOE coincides, in this case, with the interference pattern that would have been observed if the mirror had been illuminated by the point source O and by the wave phase-conjugated with respect to that to be formed at the exit of the telescope. In Fig. 1.4, this is a plane wave that comes to the mirror from infinity. In this case, the DOE has the form of concentric rings condensing to the edge of the mirror like the annular structure in Fresnel's zone plate. The total number of rings N_{max} on the mirror aperture with the diameter D and the smallest distance between the rings t_{min} for $L = R/2 = F$ (R is the curvature radius of the primary mirror), are determined, according to (1.2), by the formulas:

$$\begin{aligned} N_{max} &= \frac{D^2}{8F\lambda} = A\frac{D}{8\lambda} \\ t_{min} &= \frac{2F\lambda}{D} = \frac{2\lambda}{A} \end{aligned} \quad . (3.1)$$

For example, in the range of the aperture ratios A = (0.2 -1.0), we have from (1.3):

$$\begin{aligned} N_{max} &= (0{,}025 \div 0{,}125)\frac{D}{\lambda} \\ t_{min} &= (2 \div 10)\lambda \end{aligned} \quad . (3.2)$$

The radii of concentric rings of the DOE, on the primary mirror, are determined from condition (1.1), which, for the aperture ratio $A \leq 1$, has the form

$$r^2 = 2N\lambda F, \qquad N = 1,2,\ldots, \quad (3.3)$$

where $r = \sqrt{x^2 + y^2}$ is the radius of the N-th ring in the XOY plane, perpendicular to telescope's optical axis. From (3.3), with allowance for (3.1), we obtain the range of variation of the Fresnel's zone plate radii

$$r_{min} = \sqrt{2\lambda F}; \quad r_{max} = \frac{D}{2}. \quad (3.4)$$

Let us consider now the known methods of application of the DOE to a mirror surface.

3.1. The ruled DOE.

The ruled reflection DOE are manufactured by direct cutting of the diffraction structure on mirror surface of a workpiece. Such elements are used most widely in spectral instruments with classical, flat or concave, reflection diffraction gratings (DG) with parallel equidistant lines ruled on the mirror surfaces. Manufacturing of the ruled reflection DG involves the following stages: selection of the substrate material (usually - optical or silica glass), careful polishing of the operating surface (to within $\sim\lambda/10$), deposition of the reflecting coating (usually aluminum or gold), cutting of the diffraction grating with ruling machine, and quality control of the grating.

The main instrument for manufacturing of the ruled DG is, at present, the precision ruling machine with the interference-based control. This technology provides low level of scattered radiation and prevents from appearance of false diffraction orders (the so-called Rowland and Lyman ghosts). The main components of the ruling machine is a mechanism for feeding the workpiece and the cutting tool. The smoothness, stability, and reliability of the workpiece feed, as well as the level of vibrations of the ruling machine essentially affect the accuracy of ruling and the values of residual, periodic and local, error of division. The path passed by the cutting tool while ruling the grating measures

tens of kilometers, which sets extremely high requirements on quality and resistance to wear of the cutting tool edge. A possible solution of the problem is to use coatings from soft metals, e.g., layers of gold, or silver, or their compositions with aluminum. The process of ruling the large grating is rather time-consuming and can last as long as several days of uninterrupted operation. During this time, one has to maintain constant ambient temperature and pressure.

To illustrate the difficulties of fabrication of the telescope's primary mirror, let us estimate, for instance, the time needed for cutting the annular diffraction structure in the form given by (3.3) on the primary mirror of a Hubble-type telescope, 2.4 m in diameter, with an aperture ratio of $A = D/F = 1{:}2.33$. The total number of rings on the aperture of such a mirror at $\lambda = 1\mu m$, according to (3.1), makes up $N_{max} = 129000$. The path l passed by the cutting tool while ruling the diffraction structure, is determined by the following expression (see Eq. (3.3)):

$$l = 2\pi\sqrt{2\lambda F} \cdot \sum_{1}^{N_{max}} \sqrt{N} \,. \quad (3.5)$$

By substituting the mirror parameters and calculated value of N_{max} into Eq. (3.5), we find that the cutting tool should pass the distance $l = 630$km. For a typical cutting speed of $v = 100$mm/s, this process will take as much as 1750 hrs, which corresponds, for continuous operation of the ruling machine, to 70 days. In reality, the fabrication of such a mirror will take much longer time and is expected to be highly expensive.

The greatest number of lines per mm, $N = 2400$, was obtained on gratings up to 100 x 90 mm^2. In [39], a ruled flat DG, 170 x170 mm^2 in size with $N = 1740$ mm^{-1}, was used in the laser pulse compression system. The grating for astronomical purposes in [40] had linear dimension of 500 mm, while the

grating employed in [41] had dimensions of 400 x 400 mm^2 with the density of lines N = 1800 mm^{-1}. The greatest density of lines, in the case under consideration, will be on periphery of the mirror, and its value can be estimated using Eq. (3.1). Basing on Eqs. (3.2), for $\lambda = 1\mu m$, we obtain that the density of lines will not exceed 500mm^{-1} and is four times less at half the primary mirror radius.

Nowadays, the ruling machines provide the division accuracy and straightness of the lines sufficient to rule high-quality gratings with the ultimate number of lines N = 3600mm^{-1} for gratings of small dimensions (~ tens of centimeters). With increasing size of the grating, the ultimate number of lines per millimeter decreases. Note that the quality of a large grating is often determined by quality of the workpiece rather than by accuracy of operation of the machine. As far as we know, no information is available in the literature about fabrication of the ruled gratings with linear dimensions of more than one meter.

As was noted above, the diffraction structure on the surface of the primary mirror has the form of concentric rings (3.3), with their radii varying within the limits given by Eq. (3.4). Fabrication of the DG of this kind requires development of a new cutting technology, with translation motion of the workpiece replaced by rotational motion and controlled width of the cut. One can expect however that in this ruling technology of DOE with annular line shape, the problems of fabrication of the large-size gratings will be the same as in fabrication of classic DG and may be even simpler because of absence of reciprocating movement of the cutting tool.

3.2. The photolithography-based DOE.

Application of photolithographic technology, developed in microelectronic industry, to fabrication of the DOE makes it possible to obtain not only "shallow" binary-type profile of the DOE (typical case of low-efficiency DOE) but also a "deep" step-wise (within a single line) profile of the surface characteristic for high-efficiency DOE.

The process of fabrication of the DOE with a step-wise profile by means of lithographic technique involves, at present, several operations [34]. Using a photomask prepared in beforehand, a protoresist mask is produced on the surface of the glass substrate, and, through windows of this mask, the substrate is etched using the ionic-chemical technique. As a result, after removal of the photoresist, a binary relief structure remains on the substrate. To obtain a high-reflection DOE a set of different masks is used with windows shifted at some distance within the grating period. For each of these masks the substrate is etched at different depth to produce the needed step-wise profile of the "groove". To obtain the reflection DOE, a reflecting coating is deposited on the relief diffraction structure on the final stage of the procedure.

In fabrication of both the photo-masks for the DOE and the DOE themselves, errors are inevitable which lead, first, to distortion of the wavefront formed by the element, and, second, to reduction of the DOE diffraction efficiency compared with the calculated one. The distortion of the wavefront is entirely controlled by accuracy of drawing and reproduction of Fresnel's zones in the structure of the diffraction element, which are specified, in the case under consideration, by Eq.(3.3). Standard photolithographic equipment used for fabrication of the photo-masks for integrated circuits in microelectronics is not suitable for production of large-diameter annular structures. Nowadays, for fabrication of photomasks with axial structure described by Eq.(3.3), a special-purpose equipment is used where the drawing of the annular structure is performed on a photosensitive material using a narrow laser beam. By this

method, the diffraction lenses were produced up to 100 mm in diameter with a spatial resolution of up to 1μm in [34]. It should be noted that technological limitations in fabrication of the high-reflection photolithographic DOE are determined not by the minimal width (t_{min}) of the Fresnel zone (see (3.1)), but rather by the width of the smallest element in the step-wise diffraction structure, which is equal to t_{min}/k, where k is the number of levels in the step-wise line profile. Fabrication of the large-size photolithographic DOE (larger than 0.5 m in diameter) is limited by accuracy of fabrication of the large-scale photomask.

The most promising technique for fabrication of the large-size DOE with annular diffraction structure is likely to be the method of physical holography, in which the possibilities to register the axially-symmetric interference structure are not limited by the shape or to the size of the DOE surface.

3.3. Technology of manufacturing the static holographic DOEs.

For application of the DOE to the surface of the primary mirror,the direct ruling of the grating does not seem to be suitable, since it requires, for its practical implementation, complicated precision equipment, exact knowledge of real shape of the surface of the mirror at the moment of application of the holographic structure, and possibility to maintain this shape during the whole process of application of the structure, which can be, in some cases, as long as several days. Therefore, of practical importance is the method of fabrication of holographic optical elements based on principles of physical holography, i.e., on direct recording interference pattern of real coherent wavefronts using a recording medium applied to the surface of the mirror. Fabrication of the phase-relief DOE by methods of physical holography involves the following operations: synthesis of the recording medium, preparation of the substrate including its cleaning and application of a sublayer, application of the recording

medium to the substrate, exposure, i.e., recording of the required interference field, and photochemical processing of the exposed recording medium including, if necessary, transfer of the relief diffraction structure to the DOE substrate material and metallization of the resulting relief, i.e., application of a reflection coating.

3.3.1 Recording media used in fabrication of the holographic DOE.

Various recording media can be used for fabrication of the holographic DOE. Most popular among them are silver-halide photoemulsions, thermoplastic layers, bichromated gelatine and organic photoresists, chalcogenide vitreous semiconductors, metal and semiconductor thin films.

a) Silver-halide photoemulsions.

The use of silver-halide photoemulsions as recording media for the phase-relief holograms is discussed in papers [43 - 45]. Those papers are devoted to studies of regularities of formation of the relief structures on relatively thick (about 3 - 10 μm) layers of ultra-fine-grain photographic emulsions for holography - Kodak 649F and PE-2, as applied to their use for purposes of artistic holography. In particular, a pronounced dependence has been noticed of the height of the relief on spatial frequency of the holographic recording. For instance, as the spatial frequency of the holographic recording increased from a few lines per mm to 1100 mm^{-1}, the maximum height of the recorded relief decreased from 1 - 2 μm virtually down to zero. Basing on these data, the authors of [45] consider the spatial frequency of the order of 1000 mm^{-1} to be the ultimate one for the silver-halide emulsions.

The problems of utilization of the silver-halide emulsions for fabrication of the phase-relief DOE are considered in [46 - 49]. In this papers, important, from the viewpoint of fabrication of elements of holographic optics, features of ultrathin layers of the photoemulsion PE-2, down to 1μm thick, applied by centrifuging technique to flat and concave substrates up to 150 mm in diameter, have been studied. The photochemical processing of the exposed layers was based on selective hardening of the gelatine matrix of the photolayer and was close to the method of preparation of silver-sensitized gelatine holograms [50]. The studies of the photoemulsion layers, obtained and processed by the above method, have shown that decreasing the thickness of the recording medium reduces dependence of the height of the relief on the range of the recorded spatial frequencies and improves efficiency of utilization of the recording medium volume. It has been shown that the shape of the DOE relief profile, formed in this case, is close to the trapezoidal, approaching triangular with increasing spatial frequency. A fairly high photosensitivity of thin photoemulsion layers was noted, equal to 0.05 - 0.4 mJ/cm^2 depending on the height of the relief obtained. At spatial frequency of 1000 mm^{-1} diffraction efficiency amounted to 25%. The experimental results were described that confirmed suitability of thin photoemulsion layers for production of the phase-relief DOE, forming virtually aberrationless wavefronts. The feasibility to obtain the relief structure on thin photoemulsion layers was reported in [49] both under cw laser radiation and under second harmonic of neodymium laser with the pulsewidth 50 ns.

b) Organic photoresists.

The layers of organic photoresists, upon manufacturing the DOE, can be deposited upon the substrate both by the centrifuging technique and by method

of application described in [51]. For fabrication of the relief holographic structures, both negative and positive organic photoresists are suitable. Note that positive photoresists, i.e., the photoresists whose exposed regions acquire higher solubility, exhibit a higher resolving power (up to 3600 mm^{-1}) as compared with negative photoresists. The after-exposure processing of the photoresist layers is performed in alkaline solutions of inorganic or organic substances [52]. Table 3.1 shows holographic parameters of our domestic organic photoresists SK-17 and SK-502, developed purposely for fabrication of the phase-relief DOE [53].

Table 3.1.

Composition	SK-17	SK-502		
Wavelength of recording, μm	0,436	0,442	0,458	0,488
Exposure, mJ/cm^2	20	5	30	350
Spatial frequency, mm^{-1}	1200-3600	1250		
Layer thickness, μm	0,4-0,5			

The compositions SK-17 and SK-502 include derivatives of 0-naphtaquinonediazides, with their absorption bands expanding from 0.33 to 0.49μm with maximum in the region of 0.35 - 0.4μm.

c) Photothermoplastic materials.

The photothermoplastic (PTP) layers are characterized by fairly high holographic parameters [52, 54, 55]. Their processing takes fractions of second without using any solutions. An important feature of the PTP is their reversibility, i.e., possibility of multiple recording and erasing of the

information. One of the best investigated photosemiconducting polymers with organized industrial production is poly-9-epoxypropylcarbazole (PEPC). Based on this compound, the recording media were obtained with a panchromatic sensitivity of 0.05 - 0.1 mJ/cm^2 in the visible spectral range. On plates, 10 cm in size, at spatial frequency of 300 mm^{-1} diffraction efficiency amounted 20%. Approximately the same characteristics are shown by the PTP based on polyvinylcarbazole (PVC). The PTP materials are deposited, as a rule, by casting on a film or on rigid substrate of small size. In [57], the hologram recording on PTP deposited on substrates of glass, metal, or metallized textolite was reported.

d) Chalcogenide vitreous semiconductors.

At present, widely used in fabrication of the phase-relief DOE are chalcogenide vitreous semiconductors (CVS) of different compositions. In [56], the results of studies are presented of recording properties of the As_2S_3-based CVS-layers, 0.3 - 1.5 μm thick, thermally sputtered onto dacron and glass substrates. The holograms were recorded in the light of an Ar+-laser at the wavelength 0.488 μm. The range of recorded spatial frequencies was, in this case, 500 - 1600 mm^{-1}. The achieved optimum exposures lay in the range 1-6 J/cm^2. Diffraction efficiency of the hologram was 10%. It was reported, in [57], about higher photosensitivity of the CVS (0.1 - 0.3 J) achieved in diffraction gratings with spatial frequencies from 600 to 3600 mm^{-1}. Examples of the phase-relief DOE prepared on the CVS films are given also in [58, 59]. In paper [59], for the grating recorded in arsenic-sulphide-based glass films, the reflection coefficients were obtained not less than 70% at spatial frequency of 3600 mm^{-1} in the visible light. One of the main advantages of the CVS materials is related to high technological flexibility of their deposition onto the substrate,

which involves possibility of their application both to rigid and to flexible substrates by methods of vacuum thermal evaporation and by ion-beam sputtering.

e) Bichromated gelatine.

The relief constituent of the phase modulation on layers of the bichromated gelatine (BCG) is formed due to variations in the degree of hardening, hence, of the gelatine layer thickness in the course of the exposure and subsequent chemical processing, including the processes of swelling in water and dehydration in isopropyl alcohol. On thin layers of the non-hardened BCG, the surface relief, in the range of spatial frequencies 100 - 1000 mm^{-1}, was obtained under exposures of 150 mJ/cm^2 for the wavelength 0.488μm and of 100 mJ/cm^2 for the wavelength 0.411 μm. Besides, in [60], the relief 0.1 - 0.2 mm in height was obtained in the range of spatial frequencies 30 - 500 mm^{-1} on non-hardened BCG layers, up to 10 cm in diameter, exposed to cw radiation of an Ar-laser with the wavelength 0.488 μm (0.5 - 5 mJ/cm^2) and to pulsed radiation of second harmonic of neodymium laser (5 -10 mJ/cm^2).

f) Metal and semiconductor thin-film systems.

Upon pulsed holographic recording in thin-film systems characterized by low mechanical strength, by fairly large thermal expansion, and by high temperature of phase transition (sublimation, melting. boiling), formation of the relief is related to action of thermal stresses developed in the absorbing layer. In thin-film systems with relatively high mechanical strength, characterized by low thermal expansion and low temperatures of phase transitions, formation of the relief under exposure occurs due to thermal ablation [61]. The thin-film metal

and semiconductor systems are applied to substrates by methods of vacuum deposition. They do not require any additional processing after the exposure and are characterized by a fairly high photosensitivity in a wide spectral range including the IR region. In [62], the results of recording of diffraction gratings in various thin-film systems are presented. The photosensitivity of the studied materials achieved by the authors of the paper was 1 - 100 mJ/cm^2 upon recording in pulsed radiation with the wavelengths 0.69 μm and 1.06 μm. Maximum diffraction efficiency for the 0.2 μm thick film amounted to 10-15 %. The above characteristics of the recording media suitable for recording of the phase-relief holograms, given in this brief review, show that each of the materials considered is inherent in its own merits and drawbacks. For this reason, the choice of the recording medium, in each particular case, should be made with allowance for specific features of fabrication and operation of the required holographic DOE. In the next section we will give a review of techniques used for formation of interference patterns necessary for recording of large-scale holographic DOEs.

3.3.2. Methods of formation of interference field for recording the hologram structures on surfaces of telescope's large-scale mirrors.

In terms of its optical characteristics, the holographic structure applied to the surface of the primary mirror with the aim to read out the information about its shape in the course of operation of the telescope is an axial DOE with low diffraction efficiency [63 - 68]. Specific features of recording such a DOE are its large dimensions (as a rule, diameter of the primary mirror is larger than 2 m) and relatively small values of tolerance to mutual alignment of main elements of the recording system -substrates of the DOE and sources of the reference and object waves. In [66,67], is has been shown that when certain conditions are

satisfied on the stage of choosing principal configuration of recording and reconstruction of the DOE, it is possible to lower the needed accuracy of positioning of the reference (R) and object (O) sources and to minimize overall dimensions of the recording system retaining absolute accuracy of control of the mirror surface shape. However, even when the above conditions are satisfied, the requirements to accuracy of positioning of optical elements of the recording system, as well as to stability of their position remain fairly high. For example, the typical values of the tolerances for angular displacements of the reference, object, and reading sources are less than 1 arc second for fairly large distances (5 - 20 m) from them to the primary mirror. All this brought about the necessity to develop and to comparatively analyze the most technological methods of formation of the interference field that allow one to implement in practice the fundamental configuration of the DOE recording.

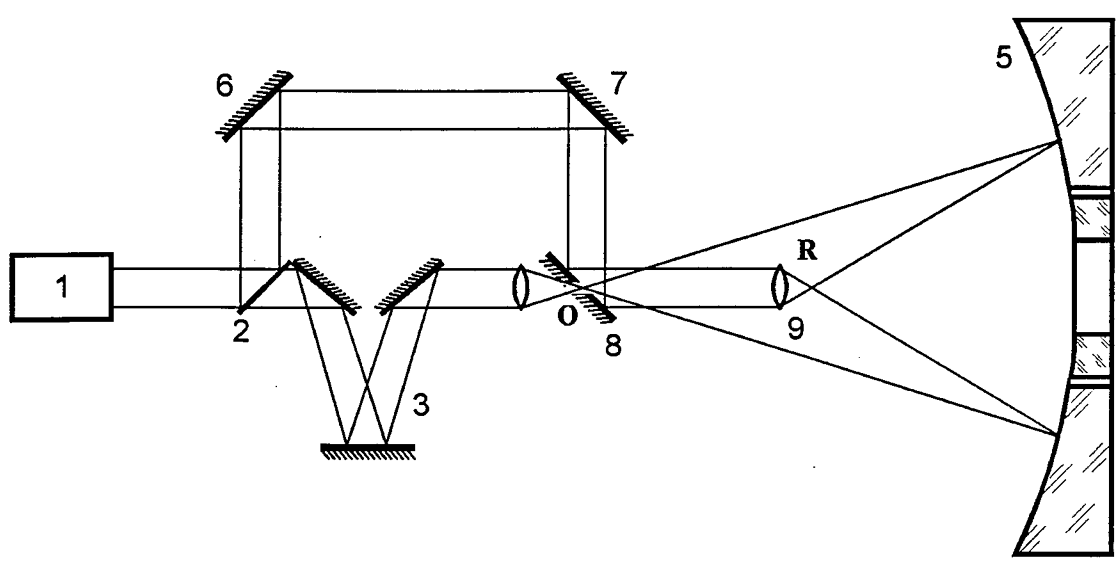


Fig.3.1. Schematic of the interferometer for recording the hologram on the surface of the primary mirror.

1 - laser, 2 - beamsplitter, 3 - delay line, 4,9 - objectives, 5 - primary mirror, 6,7,8 - flat mirrors.

The most evident and conventional way of implementation of the chosen fundamental configuration of recording of the hologram structure is to use a

double-beam interferometer with amplitude splitting of unexpanded laser beam [69]. Schematic of this interferometer is shown in Fig. 3.1. In this figure, 1 is the source of coherent radiation - a high-power single-frequency Ar-laser LGN-512 with output power in cw mode of up to 2 W at the wavelength 0.488μm. The numeral 2, in Fig. 3.1, denotes the beamsplitter forming the reference and object channels of the interferometer. The object channel of the interferometer includes the mirror system of partial compensation for the arm lengths of the interferometer (3) and objective 4 forming a real image of the object point source. The reference channel comprises plane mirrors 6, 7, 8 and objective 9 forming the reference source image. The numeral 5 denotes the primary mirror of the telescope, on whose surface, due to interference of the reference and object beams, the interference field of the needed structure is formed, which is then recorded by the photosensitive medium applied to the surface of the mirror. Among the merits of the conventional configuration of the interferometer shown in Fig. 3.1, we can mention relatively small dimensions and clear apertures of optical elements and, also, the presence of real images of the reference and object sources, which significantly simplifies alignment of the interferometer. At the same time, the above configuration exhibits a number of shortcomings. Among most essential of them is a rather large, up to tens of meters, length of arms of the interferometer and, also, the large number of optical elements in each channel of the interferometer. This imposes higher requirements to equipment hardware that should provide stability of position of the interference field in the course of the DOE recording. In particular, it becomes necessary to use a sufficiently complex adaptive optical system of phase correction [70], intended for recording of precision large-scale DOE, which require long (more than 10^2 - 10^3 s) exposure times.

The efforts to reduce the arm length of the interferometer, e.g., by introducing a 'dosed' aberration into the reference or object beam, entail

increasing aperture of the auxiliary optical elements and systems, used for this purpose in the recording system. However, it is possible to largely eliminate the drawbacks inherent in the conventional configuration considered above by using auxiliary elements and forming optical interferometric system with coincident channels. For implementation of this approach, the authors of [71] suggest to use a holographic version of the interferometer with coincident channels, where the function of formation of the reference and object beams is fulfilled by an auxiliary holographic optical element (HOE). This element can be fabricated in the form of a segmented hologram or in the form of splicing, or in the form of other combination of two independent holograms simultaneously forming the images of the reference and object sources.

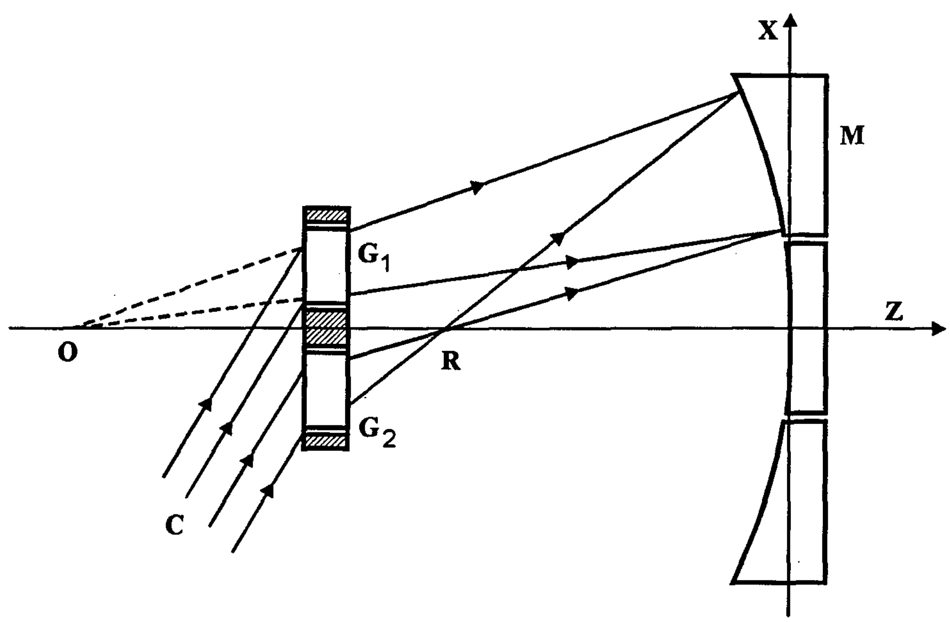


Fig.3.2. Schematic of the interferometer for forming the interferogram within a subaperture M of the segmented primary mirror.
C - reference wave, R - reference light source, O - object source, G_1,G_2 - holograms.

As an example, Fig. 3.2 shows a schematic of the interferometer with HOE intended for formation of the interference field on one sub-aperture of the telescope's primary mirror. Note that successive positioning of other sub-apertures of the mirror into position of the sub-aperture M, will make it possible

to successively cover the whole surface of the primary mirror by the holographic structure. An inevitable phase mismatch between holographic structures of different sub-apertures will have to be compensated electronically as it is done in telescopes with a wavefront sensor [66]. An advantage of the successive recording of the DOE is reduction of the exposure time by a factor of N, where N is the number of sub-apertures of the primary mirror, which are, as a rule, identical in size.

The HOE used in the interferometer under study can be made in the form of a single or two, placed into a single holder, holographic elements, which are obtained using the reference wave C and form the image of the reference (R) and object (O) by means of the holographic elements G_1 and G_2, respectively. Note that the diameters of the holographic elements G_1 and G_2 depend on the distances from the reference and object sources to the primary mirror and, also, on diameter of the sub-aperture d and are usually equal to $d/5$ - $d/10$. In the interferometer designed in this fashion, it is possible to independently correct positions of the reference and object sources forming the interference field by mutual displacement and tilt of auxiliary holograms G_1 and G_2. The abandonment of possibility to independently correct positions of the sources makes it possible, according to [71], to construct optimal, from the viewpoint of its practical implementation, configuration of the holographic interferometer with coincident channels for recording the DOE (see Fig. 3.3).

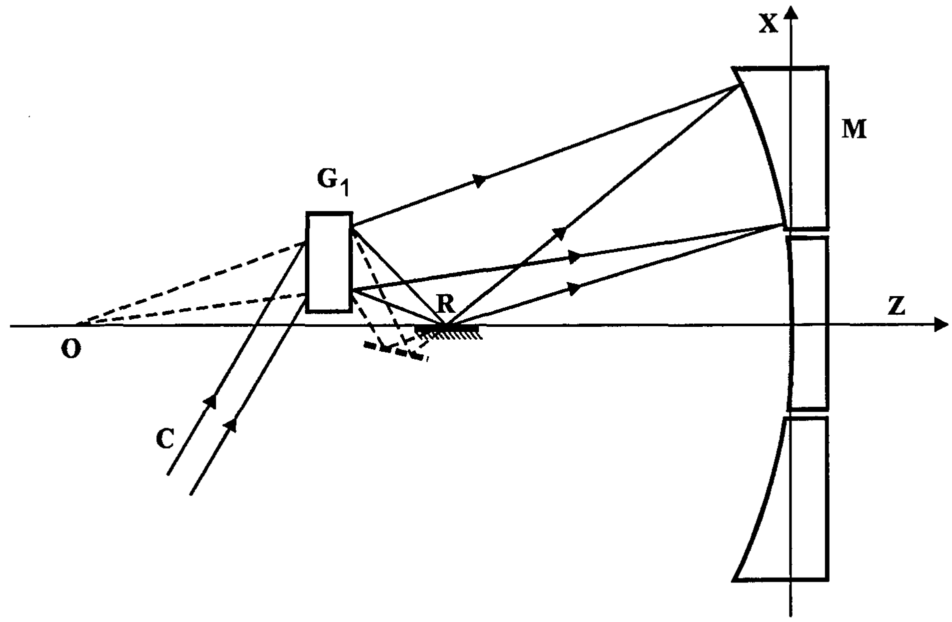


Fig.3.3. Schematic of the holographic interferometer with the coincident channels for recording DOE.

G - auxiliary hologram, R - reference source, O - object source, V - flat mirror.

The main difference between this configuration and that presented in Fig.3.2 is that formation of images of both sources (reference and object) is suggested to perform, in this system, using the same auxiliary hologram G_1 and additional plane mirror V. In this case, two arrangements of the mirror in the DOE recording system are possible. In the first case, this mirror is placed so that the optical axis of the primary mirror passes through the surface of the additional mirror, while the beam forming the image of the reference source R is focused on this surface. A drawback of placing mirror V into the laser beam focus is a possible distortion of parameters of the reference beam of rays due to local thermal deformation or damage of the mirror surface. Another configuration implies placing mirror V outside the focal plane of the reference beam so that the beam reflected by the mirror forms a real image of the reference source. The beam path and position of mirror V, for this case, are schematically shown by dashed lines in Fig. 3.3.

It is noteworthy that for the typical values of diameters of the auxiliary HOE and distance between the reference source and the primary mirror,

indicated above, the angle of incidence of the reference beam on the flat mirror is 70^0 - 80^0. At such angles of incidence, it is possible, using thermostable mirror coatings, to obtain, at the wavelength of operation, the reflectivity ~ 95%. This allows one to avoid undesirable thermal effects on the mirror when the beam is focused onto its surface by the auxiliary HOE with the aperture ratio 1:5 - 1:6 provided that the average power of the reference beam does not exceed 100 mW. The merits of the configurations with the mirror outside the focus point are, first, the absence of the above restriction to the reference beam power and, second, possibility to perform spatial filtration of the beam in this point. Among drawbacks of this arrangement of the mirror are some complication of recording system of the auxiliary HOE intended for operation with flat mirror placed in the reference beam focus.

It should be noted that the holographic method of formation of the reference and object beams by means of an auxiliary HOE reconstructed by a collimated beam, proposed in [71], makes it possible to use the technique of successive recording the interference field [72-74], which is developed fairly well and is widely used nowadays. In the case under consideration, the successive recording of the interference field is provided by parallel translation of a narrow collimated beam over the surface of the auxiliary HOE. This allows one to considerably shorten the exposure time for each of the successively recorded areas of the holographic structure and to use, for recording of the DOE, the recording media with relatively low photosensitivity.

In [71], the exposure time is estimated needed for formation of the holographic structure on one of sub-apertures of the primary mirror. The calculation was fulfilled for the following values of the parameters: the DOE clear diameter 2.4m, with diameter of sub-aperture - 0.8 m; fraction of radiation power incident on the surface of the sub-aperture with the recording medium makes up 10% of the output laser power equal to 2 W; the optimum exposure

for the media, that we consider to be most promising for development of the DOE: silver-halide layers (SHL) - 0.05 mJ/cm^2, bichromated gelatine (BCG) layers - 1mJ/cm^2, chalcogenide vitreous semiconductor (CVS) films - 3mJ/cm^2. Then, for simultaneous recording of the interference field over the whole surface of a single sub-aperture, the calculated exposure time will be: for SHL - 2 s, for BCG - 39 s, and for CVS - 118 s. In the case of DOE recording on a single sub-aperture by method of line-by-line scanning over the surface of the auxiliary HOE, the needed exposure times for each of the successively recorded regions can be at least by an order of magnitude smaller than the values given above, which makes it possible to construct large-scale DOE with high yield of acceptable samples.

Chapter 4.

Nonlinear-optical approach to generation of a dynamic DOE on a deployable or segmented primary mirror.

As shown in Chapters 1 and 2, in some configurations of telescopes with nonlinear-optical correction of distortions, phase-matching of sub-apertures of the primary mirror and compensation for its optical distortions require development of large-scale optical elements with diffraction structure applied to their surfaces.

It has been shown in Chapter 3 that contemporary technological level makes it possible, by means of optical, chemical, or mechanical techniques, to manufacture static diffraction structures (DOE) on surfaces of fairly large mirrors (up to 1000 mm). These DOEs can exhibit the needed diffraction efficiency sufficient to provide the functional performance of optical systems with distortion correction.

The main drawback of static technology of the DOE, for the case of large segmented or deployable primary mirror, is related to the needed high accuracy of matching the grating lines of neighboring segments or of deployable elements. The needed accuracy of mutual initial superposition of the grating lines and piston displacements of the segments can appear to be highly difficult to implement for dimensions of the primary mirror of several meters and high aperture ratio, since the distance between the lines on the periphery of the mirror appears to be comparable with the wavelength of the reference laser.

In the course of operation of the distortion correction system with the DOE on the primary mirror, the primary mirror aberrations are compensated, with the residual errors fully determined by deformations of the diffraction structure, some kinds of which remain uncompensated.

A possible solution of the above problems in the development of large-scale-systems with segmented and deployable primary mirrors is the technique based on creation of dynamic diffraction structures on the primary mirror.

The needed dynamic diffraction structure can be formed, for example, in a thin layer of nonlinear optical material applied to the surface of the mirror due to nonlinear action of radiation of an auxiliary pulsed laser [25]. In this case, the diffraction-structure hologram (HOE) will exist only for certain time and the correction will be performed only for that particular position of the corrected mirror (or its constituents) that took place when the current dynamic HOE was recorded on the primary mirror.

The system with dynamic HOE does not seem to have so severe restrictions on its possible size as the system with DOE, and its dynamic nature allows one to exclude the errors related to deformations of static DOE in the case of segmented primary mirror.

4.1 Requirements for HOE on the primary mirror.

When considering operation of such a compensation system with HOE on the primary mirror, a number of general requirements imposed on its elements can be formulated:

- the nonlinear-optical material for the HOE recording should exhibit high photosensitivity to the recording radiation, should have low absorption losses in the spectral range of operation of the observation system, and should allow one to apply thin homogeneous and uniform layers to large surfaces;
- output emission of the recording laser should have the degree of coherence and power sufficient to form a high-contrast interference pattern on the surface of the primary mirror, which will produce HOE with the needed diffraction efficiency in the layer of the nonlinear-optical material;

- temporal characteristics of the recording laser should provide, in combination with properties of the nonlinear material, the HOE renewal speed that would make it possible to efficiently compensate for mirror's dynamic distortions;

- the weight and overall dimensions of elements that provide formation of the HOE should be suitable from the viewpoint of requirements to the observation system as a whole.

Consider, in brief, operation of the system with HOE on the primary mirror of the telescope (Fig. 4.1) (the lens for imaging the mirror on the hologram is not shown).

Let us imagine a distorted primary mirror M, with a nonlinear layer applied to its surface, in the form of combination of two optical elements: an ideal concave mirror with focal point *F* and a thin layer of nonlinear-optical material (the gap between them is shown for better understanding). The screen has the phase retardation relief over its cross section, which produces, for a round-trip, distortions in the light wave from the remote object identical to those acquired due to reflection from the real primary mirror.

Let us consider a hypothetical case of spherical wave 2 emerging from point F (Fig. 4.1,a), and coherent wave 1, close to a plane wave, propagating from the remote point source. The nonlinear-optical medium exhibits modulation of its optical characteristics corresponding to interference pattern of waves 1 and 2. If the nonlinear-optical process is characterized by some time delay, then the dynamic HOE formed by the recording waves will retain in the photosensitive layer after the waves are switched off.

It follows from common properties of holograms that waves 1 and 2, upon diffraction on the HOE, reconstruct with no distortions the wavefronts of each other after passing through the nonlinear-optical layer.

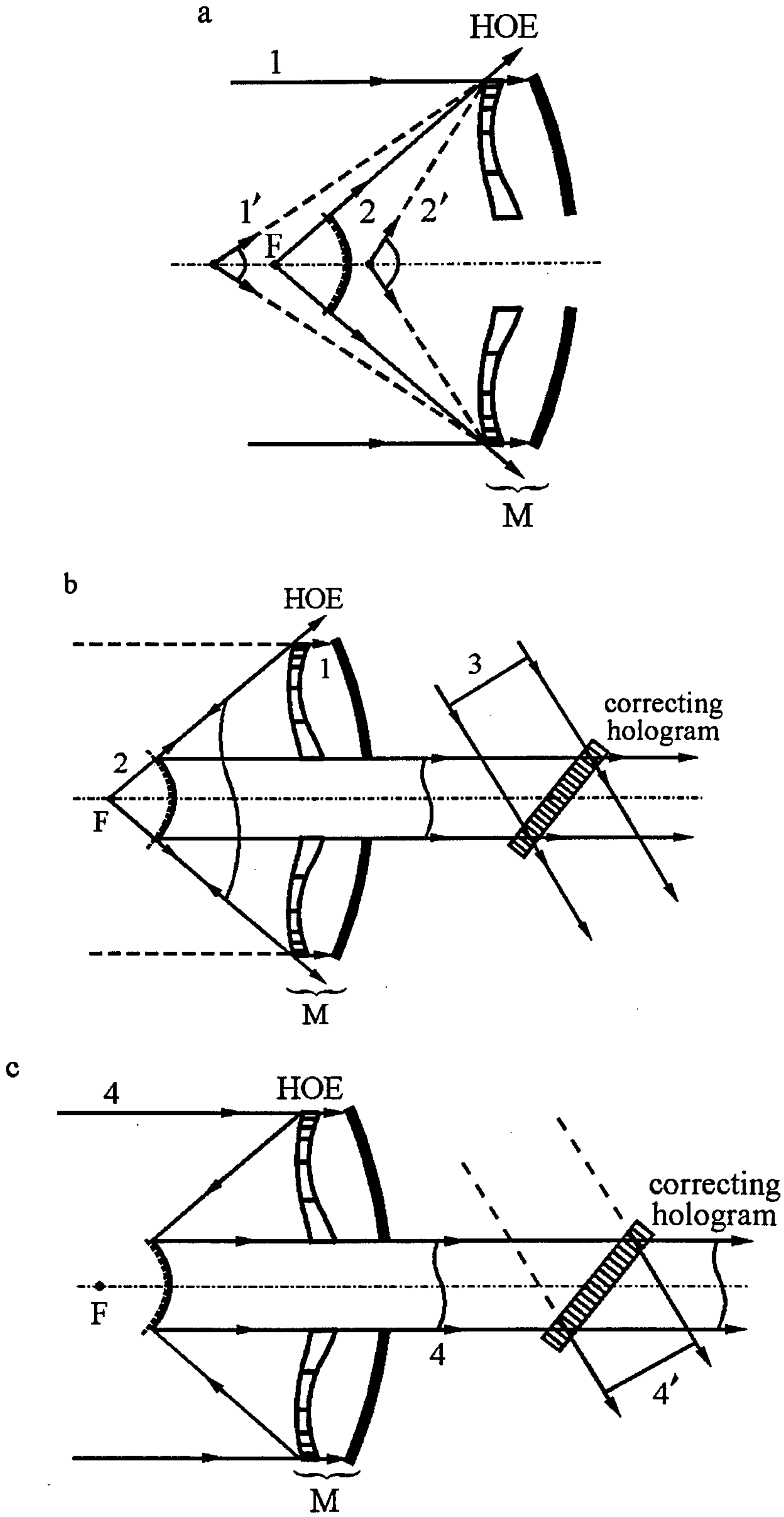


Fig.4.1. Schematic of recording/read out of HOE on the telescope primary mirror in the observing system with the use of holographic correction of distortions.

1,1',2,2',3 - coherent light waves; 4 - light wave from a remote object under observation, 4' - light wave from the remote object after compensation for optical distortions;
a - recording of a dynamic HOE on the primary mirror; b - read out of distortions of the primary mirror and recording of the dynamic correcting hologram; c - observing of the remote object with the use of distortion compensation by the correcting dynamic hologram.

Fig. 4.1,b shows the next stage of operation of the system - recording of the correcting hologram. Spherical wave 2, reading out distortions of the primary mirror, is propagating from point F and, being diffracted by the HOE, restores wave 1 from the point remote source, transmitted through the distorting screen. Then, the restored wave 1 is reflected by the mirror and passes through the screen in backward direction. As a result, in common focus *F* of the primary and secondary mirror, a distorted virtual image of the remote point source is formed. After reflection from the secondary mirror, the radiation is directed to the recording channel of the hologram, correcting the distortions, where this beam, together with plane reference beam 3, writes the hologram containing information about distortions of the primary mirror.

Figure 4.1,c illustrates the final stage - observation of a remote object. In general case this object may not coincide with the remote point-like object used for recording the HOE and differs from it by shape, position and wavelength of radiation. Light wave 4 from this remote object is reflected by the distorted primary mirror in zeroth diffraction order of the HOE, and a virtual image of the object is formed near point F. Then the beam is directed to the correcting hologram. Upon diffraction of this wave on the hologram, the wavefront from the object undistorted by the primary mirror, is restored, propagating along wave 3, since aberrations of wave 2 in the process of recording of the hologram and aberrations of wave 4 in the process of its reading out are close to each other or identical. Being focused by a lens, this wavefront gives the undistorted image of the remote object of interest.

In practical implementation of this idea, it is expedient to use, on the stage of HOE recording (Fig. 4.1,a), spherical waves 1' and 2' (rather than waves 1 and 2), with their centers of curvature positioned on the axis near point F, on both sides of it. It is important that there is no necessity, in this case, to form the beam with diameter equal to that of the primary mirror. Mutual positions of

points 1' and 2' are calculated so that the focus of the HOE is located, as before, in point F. At the stage of reading of the primary mirror distortions, as before, the probe wave 2 is used. In this case, in reconstructed wave 1, after diffraction on the HOE, additional aberrations of strongly specified type arise, controlled by geometrical conditions of the HOE recording only. These aberrations can be corrected, e.g., by placing a stationary phase corrector in the channel of reference wave 3.

The main requirements to quality of the diffraction structures, formed in nonlinear layers on the surface of the mirror for aberration compensation, are related to the needed level of intensity in zeroth and first orders in radiation reflected by the mirror and to the absence of significant distortions in the energy distribution over cross section of the beam, passed through the nonlinear layer, compared with the initial distribution. The distortions of this kind can be caused by errors in fabrication of the semiconductor layer (nonuniformity of thickness, nonuniformity of absorption of the material, surface defects, etc.). All this has to be carefully controlled in fabrication of the mirror under consideration with a photosensitive layer applied to its surface.

It is possible to use semiconductor materials as nonlinear photosensitive media, since they are characterized by a pronounced band structure. The presence of the band structure makes it possible to control optical properties of the semiconductor materials by means of external beam, namely, to change the refractive index n and the absorption coefficient α by exposing the semiconductor to a light beam [3]. The needed photosensitive layer can be obtained by the vacuum deposition technique.

For recording the dynamic light-induced diffraction structures, it is possible also to use multilayer dielectric coatings [25]. In this case, the grating is recorded by radiation efficiently absorbed the by material of the coating. When the multilayer coating is illuminated by two beams of recording radiation,

a thermal grating, corresponding to interference pattern of the recording beams, arises in the coating. With increasing temperature, both the refractive index and thickness of the coating layer change, which causes modulation of reflectivity of the multilayer dielectric reflection coating on the wavelength of the reading beam. The thermal grating can be recorded by the beams with the wavelengths somewhat different from the wavelength of the reading beam, which is absorbed by the coating.

It is noteworthy that in such a case there is always some residual error of compensation caused by the difference in the wavelengths of recording and reading out the HOE (the well known error of chromatism of the hologram). However this error is of static nature and usually can be taken into account and strongly suppressed.

It is assumed, in systems with dynamic HOE, that the recording and reading of HOE is performed during time intervals much smaller than the time of deformation of the primary mirror. For this reason, the initial deformation of the primary mirror existing to the moment of recording and connected with fabrication errors of the mirror or its segments as well as with angular or piston shifts of the segments does not influence the quality of aberration compensation.

A specific drawback of this method, when used in systems with primary mirrors of large dimensions, is related to significant power (or pulse energy) of coherent radiation needed for recording of the dynamic HOE. Since the light energy density should be constant on the surface of the mirror, the total output power of the laser source grows quadratically with dimensions of the primary mirror aperture.

Performance of the system with HOE on the primary mirror essentially depends on temporal characteristics of the primary mirror's distortions and particular nonlinear-optical mechanism of the HOE recording. For instance, fast processes in semiconductors can provide high speed of renewal of the dynamic

HOE and compensation for fast components of optical distortions in the frequency range above ~ 10^5 Hz, but will likely need a higher level of the average output power of the recording laser. On the other hand, slower nonlinear mechanisms (as, e.g., in photorefractive polimers) exhibit higher sensitivity to the recording radiation, but permit to compensate only sufficiently slow aberrations. Thus the dynamic characteristics of the HOE on the primary mirror should be necessarily matched to corresponding parameters of the correcting element of the system, no matter whether this is a PC mirror or a dynamic hologram-corrector.

4.2. Studies of distortion correction in optical systems with a HOE on the primary mirror.

The scientific literature dedicated to this problem deals only with the laser-beam formation systems [25]. However, the primary mirror distortion compensation, in such systems, has much in common with the primary mirror distortion compensation in observation systems.

This technique is most elaborated at present for the beam-formation systems of CO_2 lasers. The idea of implementation of the dynamic diffraction optical elements for the wavelength of 10.6 μm with semiconductor films of crystalline or amorphous Ge was proposed in [25]. Preliminary experimental studies, carried out with the DOE of this kind by authors of this work, showed good prospects for development of optical diffraction elements based on nonequilibrium charge carriers, generated in a semiconductor by radiation of a laser with a shorter wavelength.

As applied to the CO_2-beam-forming systems, two different technologies of HOE manufacturing have been developed [25]. One of them is based on use of a two-layer coating of metal-dielectric-semiconductor (MDS) type

(amorphous germanium -zinc sulfide) applied to the reflecting surface of the metal mirror. This technology uses a set of standard operations of optical industry.

Another method of fabrication of such a mirror, which has been also implemented, is the following: a thin plate of metallic germanium is coated with a copper reflection coating, the plate is glued by the coated side to a glass substrate, and then, by grinding and polishing, the needed thickness of the germanium layer is achieved.

The latter technology was used to fabricate a model segmented mirror for experimental studies on aberration correction with the dynamic HOE recorded in a thin Ge layer, which served as a nonlinear medium [5]. Since this study is, at present, the only example (we are aware of) of implementation of the technique of dynamic HOE on the mirror, we will consider it in more detail.

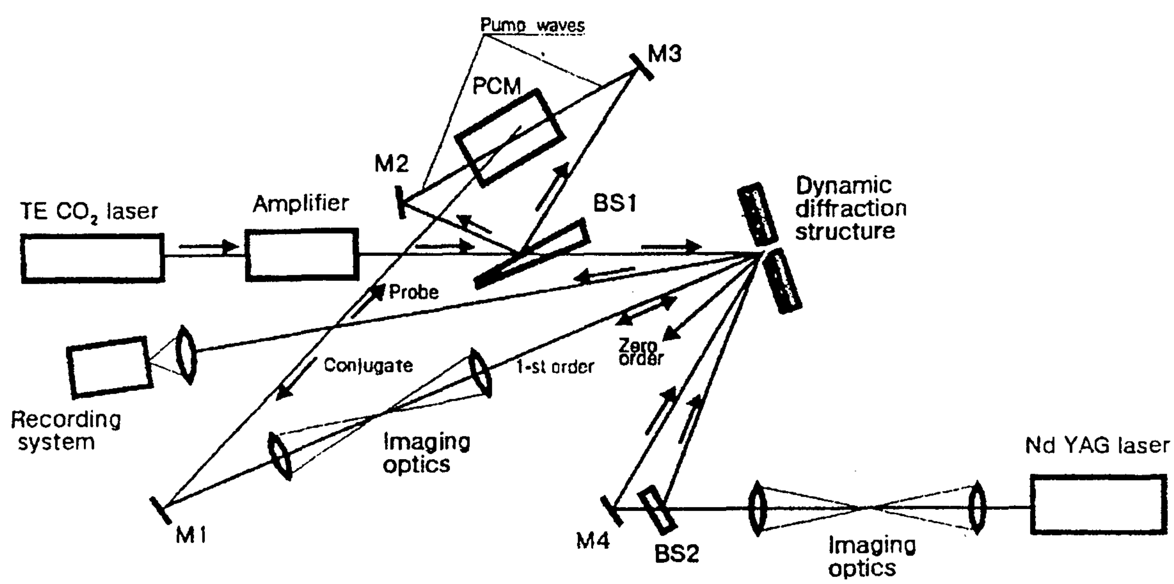


Fig.4.2. Basic optical schematic of the experiments on distortion correction with HOE on the mirror's surface.

Optical layout of the experiment is shown in Fig. 4.2. As a source of coherent radiation was used a TEA CO_2 laser comprising a master oscillator with spectral selection of the output emission and an amplifier. The high-quality

laser beam, on the line P24, had the wavelength 10.4 μm, the energy per pulse 2.3 J, and the pulsewidth of about 1μs. Two beams with total energy of 0.45 J were formed by reflecting from different sides of beamsplitter BS_1 and were used to pump the cell that produced phase conjugation by means of four-wave mixing in the nonlinear medium ($^{34}SF_6$ under a pressure of 150 Torr). The main beam from the CO_2 amplifier passed through the beamsplitter (with a pulse energy of about 0.8 J) and was directed to the two-segment mirror as a probe beam. The dynamic HOE was recorded on the surface of a germanium layer, upon interference of two beams of Nd^{3+}:YAG laser, by generation of free carriers in Ge in maxima of the interference fringes. Their total energy was approximately 0.2 J with a pulsewidth of about 0.5μs. The energy in each recording beam did not exceed 50 mJ per square centimeter of the mirror surface. In these conditions, the diffraction efficiency was approximately 1% for the CO_2 laser, so that the beam that diffracted to the minus first diffraction order and read out information about aberrations of the two-segment mirror had the energy at the entrance of the PC-cell of about 4 mJ. After reflection from the PC-cell with the efficiency about 100 %, the beam propagating backward, was reflected by the two-segment mirror in zeroth order, and was directed to the registration system for analysis of degree of correction of the two-segment mirror aberrations.

In the course of the experiments, two elements of the two-segment mirror with dynamic HOE on their surface could be tilted by some angle or could have a variable piston shift with respect to each other. The maximum angles of tilt were limited by the angle of view of the PC-mirror (approximately 10^{-2} rad) and were equal to $\theta_{max} \approx 6\lambda_2/d_2$ (4.5 mrad), where $\lambda_2 = 10.6$ μm and $d_2 = 15$ mm is the beam diameter on the HOE. The piston shifts were varied from zero to 2 mm (200λ). Under any angular tilts and piston shifts of elements of the segmented

mirror within the above range, it was possible to observe, in the far zone of the corrected beam, a single spot of radiation with the angular size close to the diffraction limit for the total beam diameter.

In these conditions, the time behavior of the dynamic HOE was controlled by the times of the free-carrier generation and recombination in Ge, which was around 10^{-7} s. Thus, the potentialities of this scheme of dynamic aberration compensation extend up to frequencies of several MHz.

In conclusion, we would like to note that the method of distortion correction using dynamical HOE on the surface of the mirror (both segmented and deployable) is a promising technique in this field of application. The experiments performed allow us to claim that it is possible not only to compensate for various optical distortions arising due to reflection from the severely distorted primary mirror, but also to phase-match its sub-apertures in a large range of their tilts and piston shifts. It is clear however that for implementation of such a technique in large-aperture observation systems the further investigations are needed aimed at development of new nonlinear-optical materials exhibiting high sensitivity to the recording light and providing the required temporal characteristics of HOE.

Conclusion

In this Report we have presented an expert assessment of the problems related to application of methods of nonlinear optics to correction of distortions in primary mirrors of the imaging telescopic systems. Such imaging systems can be used both for viewing remote objects (observation systems) and for formation of laser beams travelling large distances (beam-forming systems). As a corrector, can be used either a hologram (static or dynamic) or a system that performs phase conjugation. In the latter case, only coherent light sources can be used. In the former case, coherent radiation is needed only at the stage of hologram recording.

In the framework of the expert assessment we have done the following:

1. Different existing and possible architectures of the imaging systems, such as the 'bypass' configuration, configuration with the DOE on the primary mirror, and the hybrid system TENOCOM with the DOE on the secondary mirror of the telescope have been considered with respect to their application for correction of distortions in telescopes.

2. Simple estimates of the distortion compensation factor for different architectures of imaging systems and beam forming have been presented.

2.1. It has been shown that the system with DOE on the primary mirror possesses a certain advantage in terms of quality of distortion compensation compared with the 'bypass' configuration for the same parameters of the primary mirror.

2.2. In the case when the hologram-corrector is used for observation of a source with a broad spectrum, the main reason of residual errors of correction is the broad spectrum of the object rather than one or the other architecture of the system.

2.3. The estimates show that the system with DOE has a rather low sensitivity with respect to dynamic variations of the curvature of the primary mirror, to its tilts and other perturbations caused by thermal or vibrational effects.

3. With all parameters the same, the system with DOE on the primary mirror can be twice shorter than the system with 'bypass' configuration and TENOCOM.

4. A drawback of the system with DOE on the primary mirror is related to the absence, at present, of technology of fabrication of the DOE of needed quality for large-size mirrors. Still, we have considered different possible designs of this element.

5. An advantage of the TENOCOM system is that the needed dimensions of DOE for this system are determined by diameter of the secondary mirror of the telescope, rather than by a much larger diameter of the primary mirror.

6. One of the promising ways for development of observation systems with DOE on the primary mirror is related to dynamic recording of the DOE in a thin layer of nonlinear medium, purposely deposited onto the mirror (dynamic HOE). In this case, the quality of compensation is improved, because recording of the HOE and observation of the object are being made virtually simultaneously. The dynamic HOE are most efficient with the use of a segmented primary mirror.

The above results, as a whole, demonstrate good prospects for application of DOE in telescopic systems with distortion correction by methods of nonlinear optics and call for additional studies aimed at improvement of technology of deposition of DOE on the surface of large-size mirrors.

References

1. J. Upatnieks, A. Van der Lught, E. Leith, 1966, Appl.Opt., **5**, No4, 589-593. "Correction of lens aberration by means of hologramm"
2. Kogelnik H, Pennington K.S. JOSA 1968, **58**, 273-274. "Holographic imaging through a random medium".
3. Yu.N.Denisyuk, S.I.Soskin, "Holographic correction of distortions of the primary mirror of a telescope", Optika i Spektr., 1971, **31**, No6, 992-999 (in Russian).
4. Yu.N. Denisyuk, S.I. Soskin, «Holographic correction of distortions of an optical system caused by deformation of the primary mirror», Opt.Spektr., **33**, No5. 994-996, 1972, (In Russian).
5. Yu.E.Kouzilin, V.N. Sintsov "Holographic synthesis of the combined objective», Optika i Spektr., **36**, No3, 608-611, 1974.
6. D.M.Pepper, Opt.Eng, 1982, **21**, 156-181. "Nonlinear optical phase conjugation".
7. T.R. O'Meara "Compensation of laser amplifier trains with nonlinear conjugate techniques", Opt.Eng., 1982, **21**,243-251.
8. Yu.D.Pimenov, V.N Kouzilin et al. «Holographic correction in the objective with the segmented primary mirror», Optiko- Mekh. Promyshl., **7**, 23, 1984.
9. B.Ya.Zeldovich, N.F.Pilipetsky, V.V Shkunov 1985, "Wavefront reversal", Moscow: Nauka (in Russian).
10. Jesper Munch, Ralph Wuerker "Holographic technique for correcting aberration in a telescope", Appl. Opt. 1989, **28**, 7, 1312-1317,.
11. J.Menders, R.Aprahamian, J.Godden, 1989, Proc. SPIE, Vol. **1044**, 256.
12. J. Munch, R. Wuerker, L. Heflinger, «Wideband holographic correction of an aberrated telescope objective», Appl. Opt., **29**, 16. 2440-2445 , 1990.
13. M.V.Vasil'ev, V.Yu.Venediktov, A.A.Leshchev, G.A.Pasmanik, V.G.Sidorovich "Compensation for distortions in imaging systems via phase conjugation", Akad Nauk SSSR, Ser.phys., 1991, **55**, 260-266.
14. A.A. Leshchev, V.G. Semenov, et al. "High-aperture-ratio telescopic laser system with PC-correction of the segmented primary mirror", Kvant. Elektr., 1991, **18**, No12, 762..
15. R.B.Andreev, V.V.Volosov, V.M.Irtuganov, V.P.Kalinin, V.V.Kononov and V.E.Sherstobitov, "On PC- correction for distortions in a forming telescope with a diffractional optical element", Kvantovaya elektronika, 1991, **18**, 762-765 (in Russian).
16. M.A. Kramer, C.J. Wetterer, T. Martinez, «One- way imaging through an aberrator with spatially incoherent light by using an optically adressed spatial light modulator», Appl. Opt., 1991, **30**, No23, 3319-3323.

17.V.E. Sherstobitov, V.P.Kalinin, D.A.Goryachkin, N.A.Romanov, S.A.Dimakov, V.I.Kuprenyuk, "CO_2 lasers and phase conjugation", in A.D. Schnurr (ed.), Modelling and Simulating of Laser System, II L-A, CA, Proc. of SPIE, 1991, v.**1415**,79-84.
18.M.V.Vasil'ev, V.N.Venediktov, A.A.Leshchev, P.M.Semenov, "Laser beam forming telescopic system with output tract compensation via phase conjugation", Kvant.elektr., 1993, **20**, 317-318.(in Russian).
19.R.B.Andreev, A.G.Kalintsev, S.V.Kaminsky, L.N.Soms "Compensation for distortions of a forming telescope with a diffraction optical element on its segmented mirror", Quant.Electr., 1994, **24**, No4, 365-367.
20.V.G. Leshchev, V.G. Sidorovich, M.V. Vasil'ev, V.Yu Venediktov, G.A. Pasmanik, "Nonreciprocal optical systems with phase-conjugative mirrors-a new class of optical Imaging System" Internat. Journ. of Nonlin. Physics, 1994, **3**, 89-100.
21.H. Chakmakjian, M.T. Gruneisen, K. Koch, M.A. Kramer, V. Esch, «Time-multiplexed real- time one- way image compensation for high- frequency aberration correction», Appl Optics., **34**, No6. 1076-1080, 1995.
22.D.M.Pepper, C.J.Celestino, D.M.Mitchell, "Real-time holography, innovative adaptive optics, and compensated optical prtocessors using spatial light modulator" in book "Spatial Light Modulator Technology" U. Efron ed (Marcel Dekker, New York, 1995) p.585-665.
23.G.A. Andersen, J. Munch, P. Veitch, «Holographic correction of large telescope primaries by proximal off- axis beacon», Appl. Opt., **35**, 4, 603-608, 1996.
24.A.A Ageichik, S.A. Dimakov, O.G. Kotyaev, A.A.Leshchev, Yu.A. Resunkov, V.V. Stepanov, V.E. Sherstobitov, A.L.Safronov. "The use of dynamic holography technique for correction of aberration in telescopes"/ 1996, SPIE, v.**2771**,156-163.
25.M.P.Bogdanov, S.A.Dimakov, A.V.Gorlanov, D.A.Goryachkin et al. 1996, Opt.Comm., **129**, 405-413. "Correction of segmented mirror aberrations by phase conjugation and dynamic holography".
26.R.B. Andreev, M.V. Vasil'ev, V.Yu. Venediktov, «Experimental realization of laser telescopic system with PC-compensation for distortions», Opticheskii Zhurnal, **1**, 46-48, 1996. (In Russian).
27.S.A.Dimakov, S.I.Kliment'ev, N.A.Sventsitskaya, V.E.Sherstobitov, «Compensation for distortions of optical elements by dynamic holography techniques in white light", Optika i Spektr., **80**, 4, 699-704, 1996.
28.G.Andersen, J.Munch, P.Veith, «Compact holographic correction of aberrated telescopes», Appl. Opt., **36**, 7, 1427- 1432, 1997.
29.M.T.Gruneisen, J.M.Wolkes, «Compensated imaging by real- time holography with optically adressed spatial light modulators», *OSA TOPS*, **14**,

«Spatial light modulators», Geoffrey Burdge and Sadik C. Esener», p. 220-226, 1997.
30.V.A.Berenberg, M.V. Basil'ev et al «Correction of objective aberrations in broad spectral range by means of liquid crystaline SLM", Opticheskyi Zhourn., **64**, No9, 73-74, 1997.
31.V.Yu.Venedictov "Negative optical feedback correction for the extended range of distortion", Proceedings of SPIE, v.**3219**,133 -137, 1997.
32.V.E. Sherstobitov. "Phase conjugation of CO_2 laser radiation and its applications", R. Kossowsky et al (eds.), Optical Resonators-Science and Engineering, 119-152,1998. Kluwer Academic Publishers, Printed in the Netherlands.
33.M.P.Bogdanov, S.A.Dimakov, A.V.Gorlanov, V.M.Irtuganov, S.I.Kliment'ev, K.G.Lasunin, I.B.Orlova, A.M.Scott, V.E.Sherstobitov, N.A.Sventsitskaya, D.I.Zhuk "Compensation for distortions of telescope's primary mirror by means of a volume dynamic hologram" Proceedings of SPIE, v.**3263**, April 1998.
34. S.T.Bobrov, G. I.Graisoukh, Yu. G. Tourkevich "Optics of diffraction elements and systems". Leningrad, Mashinostroenie, 1986.
35. S.N. Koreshev Optika i Spektroskopiya, 1994, **77**, No2, 302-306.
36. A.V.Loukin, K.S.Moustafin "Physical and synthesized optical elements and their application in optical engineering". In the book "Hologram optical elements and systems". St.Petersburg, Nauka, 1994, 90-97.
37. V.Bogli, P.Unger, et al. Opt. Eng., 1988, **27**, No2, p.143-149.
38. R.J.Collier, C.B.Burckhardt, L.H.Lin, "Optical Holography", 1971, Academic Press New York and London.
39. V.E.Yashin, A.A.Mak. Proc. SPIE, 1988, v.**3291**, p.199-201.
40. E.F.Ericson, S.Matthews, et al., Proc. SPIE, 1984, v. **509**, p. 129-139.
41. R.D.Boyd, J.A.Britten, et al., App. Opt., 1995, **34**, No10, p. 1697-1706.
42. I.V.Paisakhson "Optics of Spectral devices", Leningrad: Masinostroenie, 1975.
43. J.H.Altman, Appl. Opt., 1966, **5**, No10, p. 1689-1690.
44. H.M.Smith, JOSA, 1968, **58**, No4, p. 533-539.
45. A.D.Galpern, I.V. Kalinina, et al. Optika i Spektr., 1986, **60**, No5, 1040-1042.
46. E.B.Brouy, S.N Koreshev, Optika i Spektr. 1989, **67**, No 3, 685-688.
47. S.N. Koreshev, S.V.Gill, Optika i Spektr. 1990, **68**, No2, 422-426.
48.S.N.Koreshev, S.V.Gill, O.A. Anikeeva, Optika i Spektr. 1990, **69**, No6, 1371-1376.
49.S.N.Koreshev, T.Ya.Kalnitskaya, B.S.Gouba, Optika i Spektr. 1992, **72**, No5, 1201-1205.

50.W.R.Graver, J.W.Gladolen, J.W.Eastes "Phase holograms formed by silver, halide (sensitized) gelatine processing" Appl. Opt., 1980, **19**, No9, 1531-1536.

51.U.Moro "Microlitographiya", Moscow : Mir, 1990.

52.J.Gladden, R.Laity, "Registering media" in book "Optical Holography" ed. by G.Kolfild, Mir, 1982.

53.A.A.Yastrebov et al. Troudy 5 Vsesoyuznoi konferentsyi po golografyi, Riga, 1985, 383-384.

54.Yu.A.Cherkasov, in book "Properties of light-sensitive materials and their application in holography, ed. by Barachevskiyi V.A., Moscow: Nauka, 1987.

55.Kryukov "Photothermoplastic recording holograms on a rigid substrate", Opiko-Mechan. Promyshl., 1991, No3, 12-15.

56.N.A.Alimbarashvily, A.D.Galpern, G.G. Dekanozishvily et al. "Study of posibility to use As_2S_3 -based films while recording imaging phase-relief holograms", Optika i Spektr. 1989, **66**, No4, 943-945.

57.T.I.Blozhevich, M.P.Kit, et al. Materialy 6 Vsesoyuznoi konferentsiyi po golografiyi, Vitebsk, 1990, 127-128.

58.Zagorskaya, I.I.Kyzhanovsky et al. "recording relief holograms in film and monolithic structures Ag chacogenide-chalcogenide glass" Uspekhy nauchnoi fotografii, 1990, **26**, 84-88.

59.R.R.Gerke, S.N. Koreshev et al. "Hologram optics in Vavilov Institute", Opticheskyi zhournal, 1994, No1, 26-39.

60.M.A.Gavrilova, B.S.Gouba et al. "Application of pulsed Nd-laser for obtaining phase-relief holograms", Materialy Vsesoyuznoi konferentsiyi "Laser Optics" 1990.

61.Haiser "Materials for optical recording in real time scale" in book "Optical disk systems", Moscow: Radio i svyaz, 1991.

62.M.D.Lavrentovich, I.I. Peshko et al. "Obtaining of static holograms with ultimate parameters in metallic films", Pisma v Zh. Tehn. Fiz., **15**, No5, 78-81.

63.Erickson, Proc. SPIE, 1980, v. **240**, p. 28-40.

64.V.S.Zuyev, E.P.Orlov, V.A.Sautkin, Kvant. Elektron., 1975, **2**, No1, 78-98.

65.M.A.Gan, B.A.Ermakov, Es'kov D.N. et al. Troudy Vavilov State Inst., 1989, **74**, No208, 42-54.

66.V.V.Anishchenko, S.N.Koreshev et al. Optika atmosfery i okeana 1993, **6**, No12, 38-46.

67.S.N.Koreshev, Optika i Spektr., 1994, **76**, No1, 109-115.

68.S.N.Koreshev, Optika i Spektr., 1994, **76**, No1, 116-120.

69.M.A.Gan, I.S.Potemin, Optiko- Mekh. Promyshl., 1990, No10, 20-23.

70.M.V.Tyutchev, E.V.Kalyashov, A.P.Pavlov, Opticheskyi Zhournal 1994, No11, 89-95.

71.S.N.Koreshev, V.S.Obraztsov, M.V.Tyutchev, Opticheskyi Zhournal 1995, No10.
72.L.F.Mollenauer, W.I.Tomlinson, Appl. Opt., **16**, No3, 555-557.
73.M.P.Kit, A.F.Skochilov, Optiko- Mekh. Promyshl., 1987, No6, 4-6.
74.G.N.Buinov et al., Optiko- Mekh. Promyshl., 1988, No6, 50-52.